Essentials of a national nitrate leaching index assessment tool

A GUEST RESEARCH EDITORIAL BY CONSERVATION PROFESSIONALS

ABSTRACT: Nitrogen (N) inputs are essential for increasing yields and maintaining the economic viability of farming systems worldwide. Although best irrigation and N management practices have been used, increases in worldwide use of N fertilizers combined with average N use efficiencies of 50 percent have contributed to increased leakage from the N cycle (e.g., higher nitrate-nitrogen (NO$_3$-N) leaching losses). Specific land use patterns have been correlated with higher NO$_3$-N concentrations in underground water resources. There is a critical need to continue improving best management practices to reduce NO$_3$-N leaching losses, increase the economic viability of farming operations, and conserve water quality.

To help meet these objectives, this paper recommends the essentials for the development of a national NO$_3$-N leaching assessment tool. The resulting NO$_3$-N leaching index (*NLI*) should be based on hydrological soil properties and climate, must consider management practices and associated crop rotations, and incorporate off-site effects. Development of the *NLI* should include the use of simulation models and expert systems; databases for soils, climate, and management; and use of the Internet. The index also needs to allow input of local site-specific information from producers and field personnel. The index needs to be national in scope and yet flexible enough for use in specialized or difficult cases. Routine use of the index needs to be kept simple and quick with minimal input from the user so that field office personnel can apply the tool on a regular basis. Application of the *NLI* should be linked to the phosphorus (P) index so that management of key nutrients—N and P—can be accomplished simultaneously.

We recommend a 3-tier approach to developing the *NLI* that would provide a uniform index yet allow for refinement of accuracy in the index values as necessary to meet study needs. Tier 1 would involve the initial use of an expert system to separate *medium, high,* and *very high* NO$_3$-N leaching potentials from *low* and *very low* potential levels by qualitatively screening non-numeric inputs obtained from users. This initial screening technique is similar to that used to develop the P index, but would be designed specifically for NO$_3$-N leaching. Tier 2 would involve computation of the NO$_3$-N leached (*NL*) index using application models or databases based on models, followed by introduction of off-site effects and local interpretation and normalization to produce the final *NLI*. In difficult cases, a tier 3 study involving detailed research models and field data would be needed along with the off-site effects, interpretation, and normalization. The *NLI* could be used routinely in conjunction with the P index to allow alternative management scenarios that optimize both N and P for maximal economic return while protecting the environment.

Keywords: Nitrate, nitrate leaching index, nitrogen, underground water, water quality

Several authors have reported a correlation between land use patterns and higher nitrate-nitrogen (NO$_3$-N) concentrations of underground water resources (Hallberg 1989; Juergens-Gschwind 1989; Fletcher 1991; Wylie et al. 1994; Hall 1996). These authors have identified excess nitrogen (N) inputs as potential sources of NO$_3$-N that can be leached out of the root zone and impact underground water resources. Animal operations and even leaching from old septic tanks have been correlated with the movement of NO$_3$-N to underground water (Hallberg, 1989). Hallberg (1989) reported that natural systems have on average less than 2 mg NO$_3$-N L^{-1} (2 ppm NO$_3$-N). Madison and Brunett (1985) reported that NO$_3$-N originating from human activities that has been leached and transported into underground water bodies can increase the NO$_3$-N concentrations beyond background levels and can cause groundwater NO$_3$-N to exceed 10 mg NO$_3$-N L^{-1} (10 ppm NO$_3$-N). Hallberg (1989) reported that the distance from the source of the leached NO$_3$-N to the water bodies is correlated with the impact. For example, at a national level, shallow wells less than 30 m (98.4 ft) deep had 50% of their reported concentrations at higher than 3 mg NO$_3$-N L^{-1} (3 ppm NO$_3$-N). The frequency of concentrations greater than 10 mg NO$_3$-N L^{-1} (10 ppm NO$_3$-N) increased to more than 70% for the shallower wells. All states have reported higher NO$_3$-N levels than those observed in natural systems (Hallberg 1989; Fletcher 1991).

Marvin J. Shaffer is soil scientist at the U.S. Department of Agriculture-Agricultural Research Service- Northern Plains Area (USDA-ARS-NPA) Great Plains Systems Research Unit in Fort Collins, Colorado.

Jorge A. Delgado is soil scientist at the USDA-ARS-NPA Soil Plant Nutrient Research Unit in Fort Collins, Colorado.

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The U.S. Environmental Protection Agency (USEPA) reported that drinking waters with levels greater than 10 mg NO_3-N L^{-1} (10 ppm NO_3-N) are unsafe for humans (USEPA 1989). Follett and Walker (1989) and Follett and Follett (2001) reported that there are several health concerns about drinking water with greater than 10 mg NO_3-N L^{-1} (10 ppm NO_3-N), including methemoglobinemia. About 50% of the U.S. population uses underground water resources as their source of drinking water (Sogbedji 2000), making it imperative that we reduce nonpoint sources of NO_3-N and their transport to underground water.

Even though it is almost impossible to eliminate NO_3-N leaching due to irrigation and precipitation events (Pratt, 1979), several authors have reported that leaching losses from agroecosystems can be kept to a minimum (Smika et al., 1977; Hergert, 1986; Westerman et al., 1988; Schepers et al., 1995; Thompson and Doerge, 1996a & b, Delgado et al., 2001). Producers should use best management practices that properly credit NO_3-N in irrigation water (Bauer et al., 2001; Delgado 2001a & b). Best management practices not only can reduce NO_3-N leaching, but they can also potentially be used to mine or scavenge NO_3-N from underground water systems (Delgado, 2001a & b; Delgado et al., 2001).

The greatest potential for mass transport of "problem" N (NO_3-N, N_2O, NO_x, and NH_3) from agriculture to the environment occurs with conversion of N to the NO_3-N form in the crop root zone and subsequent leaching to shallow aquifers (Kronvang et al., 2001). These aquifers may drain into the surface stream network via man-made or natural drains (subsurface or surface), or the aquifers may discharge directly into streams and lakes. NO_3-N from discharge of agricultural nonpoint sources into the Mississippi drainage has been implicated in hypoxic conditions in the Gulf of Mexico (Goolsby et al., 1999; Schilling and Libra, 2000). In the Midwest region, a significant amount of this NO_3-N contribution originates from agricultural drain discharges (Schilling and Libra, 2000; Randall and Mulla, 2001).

Overland flow of water and associated soil erosion from agriculture can also move N into surface water bodies. Agricultural N can also be lost to the atmosphere in the forms of N_2, N_2O, NO_x, and NH_3. Emissions of N_2O and NO_x greenhouse gases have been implicated in global climate change (Barton and Schipper, 2001; Maggiotto et al., 2000). NH_3 emissions generate odor problems, may contribute significantly to N deposition, and may cause forest decline and species changes (McCrory and Hobbs, 2001; Ni et al., 2000; Sharp and Harper, 2002).

Sharpley et al. (2001) reported that U.S. agricultural systems evolved from net P sinks to net P sources, particularly because of intensive livestock agriculture, one of the main P contributions to U.S. water bodies. The P index was developed to help identify areas with high potential for P transport and to contribute to P nutrient management (Sharpley et al., 1999; 2001). Since the main mechanisms for N and P dynamics and transformations in soils are different, as well as the mechanisms for N versus P losses, there is the need to develop a separate index for N. Sharpley et al. (1999) reported that if manure applications are based on crop N needs and manure N content, soil P concentrations will be built up to excessive levels, increasing the potential for off-site transport of P. On the other hand, they reported that if the P index is used, and conservation tillage practices that reduce off-site P transport and runoff are implemented, NO_3-N leaching may increase due to an increase in water infiltration. Although Sharpley et al. (1999) identified the need for a framework to manage N and P export from watersheds, a corresponding national NO_3-N leaching index that accounts for management practices and that can be used simultaneously with the P index has not been developed. Data presented by Eghball et al. (2002) clearly show that significant amounts of the N and P present in compost or manure organic sources will be available for crop uptake. It is also clear from Delgado and Follett (2002), Follett and Delgado (2002), and Sharpley et al. (2001; 1999) that the dynamics of N and P and their flows and transport in agricultural ecosystems are different.

Field staffs, consultants, and farmers need a simplified NO_3-N leaching index as a screening or assessment tool to quickly estimate the vulnerability of agricultural fields to NO_3-N leaching that could contaminate underlying aquifers and enter adjacent streams and lakes. The complexities of the N cycle with its many potential sources and sinks for N make calculation of a reliable quantitative NO_3-N leaching index essentially impossible without the use of computer simulation model(s) and reliable databases for soils and climate.

The NO_3-N leaching index should be designed for simultaneous use with a P index to better coordinate the management of these two essential macronutrients. Jokela (1999) has attempted to make simultaneous application of the P index and the leaching index (LI) (Pierce et al., 1991) by developing an expert system approach for Vermont. Much additional work is needed along these lines to allow a national NO_3-N leaching index to function with the P index.

Eventually, the NO_3-N leaching index should be generalized into an environmental N loss index including NO_3-N leaching, N losses from surface runoff and erosion, and atmospheric losses as N_2O, NO_x, and NH_3. For this paper, however, we will limit discussions to the first phase, namely the NO_3-N leaching index.

Preliminary leaching index work

Leaching Index (LI). Previous work has developed a range of model-based N leaching indices that have attempted to account for various soil, climate, management, and off-site factors that influence NO_3-N (Williams and Kissel, 1991; Pierce et al., 1991; Shaffer et al., 1991). Considerable experience has been gained with applications involving these indices, and each one has its own strengths and weaknesses. The U.S. Department of Agriculture-Natural Resources Conservation Service (NRCS) has made use of the *Leaching Index (LI)* (Williams and Kissel, 1991; Pierce et al., 1991; van Es et al., 2002) as a measure of potential NO_3-N leaching based on estimated water available to leach. The *LI*, also called the Nitrate Leaching Index by some authors (van Es et al., 2002), is actually a water percolation index designed to identify fields susceptible to NO_3-N leaching due to deep percolation of water. Williams and Kissel (1991) used a storage routine to account for the major effects of soil, crop, and climatic factors, using the following equation:

$$SW_1 = SWO_1 \exp^{(-\Delta t / TT_1)} \qquad (1)$$

where SW_1 and SWO_1 are water content at the end and start of time interval Δt and TT_1 is the travel time through layer $_1$. By using a water budget that accounted for crop evapotranspiration and water inputs, the percolation events were calculated when the water content exceeded the field capacity of the soil. To complete the water budget, this percolation model is connected to an evapotranspiration model.

Advantages of LI. This index can be computed using soil, precipitation, and irrigation data from available databases. There are nomographs available for *LI* according to the precipitation for the four hydrological groups (Pierce et al., 1991).

Disadvantages of LI. *LI* is not tied to N management practices, N dynamics, N sinks, N uptake, or N sources. It does not estimate the actual presence or leaching of NO_3-N. There is no estimate of how management practices or crop rotations that can scavenge residual soil NO_3-N impact net NO_3-N leaching from agricultural systems. van Es et al. (2002) reported that this method does not accurately evaluate the NO_3-N leached, since it does not account for management practices that affect NO_3-N.

Movement Risk Index (MRI). The *Movement Risk Index (MRI)* (Shaffer et al., 1991) is a water (or solute) movement risk index based on water available for deep percolation and the properties of the soil. This index is based on the following equation:

$$MRI = 1 - \exp[(-k)(WAL)/(POR_1 + POR_2)] \quad (2)$$

where k is the leaching coefficient (unitless); WAL is the water available to leach; POR_1 is the porosity of the top foot; and POR_2 is the porosity of the lower horizon. If no leaching occurs, the *MRI* will be equal to zero. If all the NO_3-N available to leach moves out of the horizon, the *MRI* will be one.

Advantages of MRI. The WAL component is calculated based on a detailed water budget for the soil profile. *MRI* provides a graduated estimate (0-1 range) of the relative amounts of NO_3-N (if present) that would be expected to leach from the crop root zone.

Disadvantages of MRI. The index does not estimate the actual presence or leaching of NO_3-N and is not tied to N management or sources and their interactions with crop N uptake and leaching events. *MRI* does not account for N dynamics, N sinks, N sources, or crop rotations.

Nitrate-N Available for Leaching (NAL). The *Nitrate-N Available for Leaching (NAL)* index (Shaffer et al., 1991) estimates the mass of NO_3-N available to leach from the soil (on a monthly or annual basis). The index takes into account the sources and sinks of NO_3-N over the time period, using the following equation:

$$NAL = N_f + N_p + N_{rsd} + N_n - N_{plt} - N_{det} - N_{oth} \quad (3)$$

where N_f is N from fertilizers; N_p is NO_3-N from precipitation or irrigation water; N_{rsd} is residual NO_3-N in the soil profile; N_n is NO_3-N from nitrification of NH_4; N_{plt} is N uptake from plant; N_{det} is NO_3-N minus loss to denitrification; and N_{oth} is NO_3-N loss to erosion and runoff.

Advantages of NAL. The index accounts for N sources and sinks (other than NO_3-N leaching), so it will account for the effects of crop rotations and some N management practices.

Disadvantages of NAL. The index does not account for movement of NO_3-N in the leachate, or water balances. This index does not account for soil hydrological properties, water budgets, irrigation, or precipitation events. The *NAL* does not account for distance to water bodies or other off-site considerations. Resource managers sometimes confuse *NAL* with the *RN* index defined below.

Residual NO_3-N (RN). The *Residual NO_3-N (RN)* index (Shaffer et al., 1991) represents the summation of NO_3-N in the crop root zone at the end of the growing season. This index has been correlated with NO_3-N leached during the non-cropped (fallow) portion of the year (Chichester, 1977; Owens et al., 2000). *RN* is similar to *NAL* as a vulnerability index, but *RN* is taken at a point in time, while *NAL* is based on a period of time (usually 1 year or 1 month).

Advantages of RN. This is simple index that can be easily measured in the field or calculated with a nitrogen budgeting model. Many areas of the Midwest tend to leach NO_3-N during the winter and spring months.

Disadvantages of RN. Off-season leaching is not always a major contributor to annual NO_3-N leached. For example, irrigated systems in semi-arid regions are often more at risk for NO_3-N leaching during the growing season and may not have much residual NO_3-N left when the crop is harvested (already leached or taken up by the crop). Effective use of RN as a leaching index is limited to certain regions and/or cropping systems.

Nitrate-N Leached (NL). The *Nitrate-N Leached (NL)* index (Shaffer et al. 1991) represents the mass of NO_3-N leached from the bottom of the crop root zone during a one-year period. Usually, the amount of NO_3-N leached is given for dynamic steady-state conditions. The NLEAP model uses Equation 4 below to compute NL.

$$NL = (NAL)\ \{1 - \exp[(-k)(WAL)/POR_2]\} \quad (4)$$

Pierce et al. (1991) used a simplified procedure to compute *NAL* and substituted LI for WAL in Equation 4. Other N models use algorithms that are different, but functionally similar to Equation 4 when they calculate NL (Ma and Shaffer 2001).

Advantages of NL. Numerical calculation of NO_3-N leached below the crop root zone is done based on water and N budgeting for the soil profile both under a growing crop and during fallow periods. The NLEAP *NL* calculation integrates the *NAL* and *MRI* indices. Regardless of model, the *NL* index accounts for management, soils, and climate factors, water and solute movement, crop N uptake, N dynamics, N sinks, N sources, and crop rotations. *NL* has been correlated with NO_3-N concentrations in shallow underlying aquifers (Wylie et al., 1994; 1995; Hall, 1996).

Disadvantages of NL. The index is not directly tied to off-site factors that control the fate and transport to aquifers, streams, and lakes. This index is based on a series of complex algorithms that usually need at least an application level simulation model.

Nitrogen Use Efficiency (NUE). The *Nitrogen Use Efficiency (NUE)* index (Bock and Hergert, 1991; Shaffer, 1997) estimates the percentage of applied N that is taken up by the crop.

Advantages of NUE. In some soil-crop systems, *NUE* values are highly correlated with NO_3-N leached. For example, Shaffer (1997) found that simulated *NUE* was correlated ($r^2 = 0.75$) with NO_3-N leached in an irrigated system in eastern Colorado.

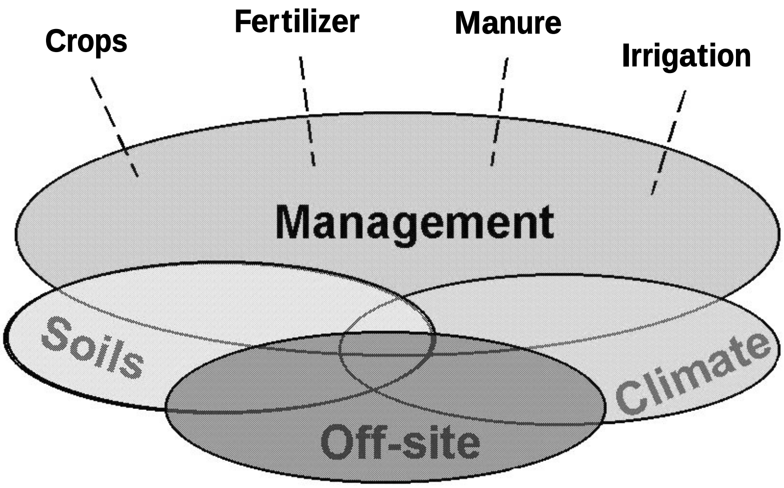
Disadvantages of NUE. Measurement of *NUE* in the field requires complex methods usually involving tracers. Simulation of *NUE* is feasible, but few models have this capability. Only a limited number of soil-crop systems have *NUE* values that are well correlated with NO_3-N leached. Situations where significant N losses to denitrification, ammonia volatilization, or immobilization occur or where NO_3-N is being stored in the crop root zone would have low *NUE* correlations with NO_3-N leached.

Annual Leaching Risk Potential (ALRP). The *Annual Leaching Risk Potential (ALRP)* index (Pierce et al., 1991; Shaffer et al., 1991) takes into account the *NL* index, plus off-site factors controlling the fate and transport of NO_3-N to aquifers using the equation,

$$ALRP = f\ (NL_y, TT, PA, VA) \quad (5)$$

Figure 1

Essential components on NO_3-N leaching index (NLI).



where NL_y is the quantity of the NO_3-N leached form the root zone; TT is the travel time to reach the aquifer; PA is the position of the aquifer; and VA is the vulnerability of the aquifer.

Monthly time steps are not recommended because individual precipitation and irrigation events are not included. The *ALRP* index will account for travel time to the aquifer, aquifer position, and aquifer classification (sensitivity).

Advantages of ALRP. The *ALRP index* integrates *NL* with underground off-site factors, giving a combined estimate of the many factors needed in a nitrate-N leaching index.

Disadvantages of ALRP. Users have had trouble identifying off-site factors and relating to implications of index values; off-site factors are fixed; index requires an application level simulation model or detailed bookkeeping to make calculations for *NL* using event-based or daily time steps.

Aquifer Risk Index (ARI). The *Aquifer Risk Index (ARI)* (Shaffer et al., 1991) estimates the risk of a shallow aquifer exceeding EPA standards for NO_3-N, using the following equation:

$$ARI = 0.369\,[N_o + (NL)(A) + N_{s1} - N_1]/AMV \qquad (6)$$

where AMV is the aquifer mixing volume; N_o is the initial NO_3-N content of the AMV; NL is the soil NO_3-N leached to the aquifer; A is the area of the field (farm); N_{s1} is the NO_3-N entering the aquifer from sources outside of the farm; N_1 is the NO_3-N that is leaving the aquifer with pumped water, tile drainage.

Advantages of ARI. Index estimates impact of NO_3-N leaching on an underlying shallow aquifer.

Disadvantages of ARI. Index requires shallow aquifer information that may be difficult to obtain. The aquifer model may be too simplistic. Calculation of the *ARI* requires an application level simulation model for *NL*.

Important influences on a nitrate-N leaching index

A national NO_3-N leaching index assessment tool should be capable of conducting a quick index assessment parallel to those conducted for other essential nutrients (e.g., the P index). The NO_3-N leaching index needs to identify the high risk NO_3-N leaching areas and the potential for NO_3-N transport to susceptible underground water resources. A NO_3-N leaching index analysis will not necessarily be equivalent to a N use efficiency (NUE) analysis, unless the main mechanism for N losses from the system is NO_3-N leaching. For example, a high NO_3-N leaching index will mean that there is the need to improve N management to reduce NO_3-N losses. If the main mechanism for N losses in such a case is NO_3-N leaching, then a higher NO_3-N leaching index will be indicative of a lower N use efficiency and large NO_3-N leaching losses. Mitigation alternatives that reduce NO_3-N leaching losses will most probably have similar impacts in reducing N losses and increasing N use efficiencies.

But due to the complexity of the N cycle, a lower NO_3-N leaching index does not necessarily mean lower N losses from the system. Other mechanisms such as NH_3 volatilization from surface broadcast urea applied to alkaline soils and denitrification of NO_3-N from flooded fine-textured or slowly-permeable soils can be sources of higher N losses. Under these scenarios where other mechanisms contribute to significant losses of N from the system, a lower NO_3-N leaching index will not necessarily mean greater N use efficiencies.

Evaluation of the NO_3-N leaching index should consider the N cycle, with its many potential sources and sinks. Computer simulation model(s) using reliable databases for soils and climate will have to be used to calculate a quantitative NO_3-N leaching index. Strong computer simulation model(s) combined with an expert system analysis of the NO_3-N leaching index will allow the analysis of total N losses from the system as well as the cropping system N use efficiencies, where appropriate. When evaluating the effect of best management practices on N use efficiencies, it is recommended to have a complete analysis of the effect of crop rotations on net NO_3-N leaching (Delgado, 2001a).

Management factors have emerged as being dominant in determining the potential for NO_3-N to leach, especially when long-term impacts are involved (Delgado, 1998; Delgado, 2001a & b; Meisinger and Delgado, 2002; Shaffer et al., 1994; Shaffer, 2002). Computer simulation model(s) used to make reliable quantitative calculations of the NO_3-N leaching index should be run considering the crop-rotation accounting for variable rooting depths. For example, rotating deeper rooted crops such as winter cover crops with shallower rooted crops such as lettuce can recover large amounts of NO_3-N previously leached out of the root zone of the shallower rooted crops (Delgado, 1998; Delgado et al., 1999; Delgado, 2001a; Dabney et al., 2001). These large amounts, up to 300 + kg NO_3-N ha^{-1} (267.8 + lb NO_3-N ac^{-1})can be recycled to the surface horizon. It is also important to credit NO_3-N added to irrigated fields with irrigation water since there is potential to mine and recover NO_3-N from underground water (Delgado, 2001a).

Figure 1 illustrates the primary considerations for a general NO_3-N leaching index: management, soils, climate, and off-site effects. Movement of water below the root

Table 1. Essentials of a national nitrate-N leaching index *(NLI)* developed on an expert system platform with strong emphasis on management as well as basic soils, climate, and off-site factors. The initial tier 1 should be viewed as a screening tool, with access to various models as needed for quantitative estimates at tiers 2 and 3.

I. An Expert system platform must:
1) be firmly grounded with basic components such as management, soils, climate, and off-site factors.
2) be based on applicable existing technology.
3) accept site-specific information from producers and field personnel.
4) be able to quickly link to modeling studies for tier 2 semi- to quantitative analyses.
5) provide qualitative tier 1 index values that have been validated.
6) be quick and easy to use.

It should also:
7) have fast configuration for the important parts of a regional/local analysis.
8) include the effects of time—initial versus steady-state effects.
9) be accessible from the Internet (web-based).

II. Management concerns are:
1) framework must be applicable nationally.
2) needs to quickly distinguish the problem areas from the minimal problem areas.
3) long-term management effects are important.
4) should include the effects of the timing of fertilizer, manure applications, and other N management.
5) must have allowances for regional and local customization.
6) underlying data must be a combination of field data and model simulations.
7) N and P indexes should not be treated as independent.
8) should consider risk assessment.

III. Soils databases:
1) should consider the potential leaching of residual nitrates.
2) should include the effects of soil spatial and temporal variability.
3) must access national soils databases from the web.
4) must access national soil management databases from the web.

IV. Climate databases must access national climate databases from the web.

V. Off-site factors:
1) should allow GIS analysis of soils across fields, fields across farms, and watershed effects.
2) should include consideration of potential off-site impacts (eg. shallow vs confined aquifers).
3) should consider the proximity to streams, lakes, karst areas, and riparian buffers.
4) should consider drinking water supplies and tile drained areas.

zone is also important; N leaching cannot occur without deep percolation of water. In this diagram, management is shown to be of primary importance, but is tempered by soils, climate, and potential off-site effects. Management considerations such as crop types (Delgado, 2001a), varieties and rotation systems (Delgado et al., 1998a & b), fertilizer and manure applications and timing (Delgado et al., 1996; Shoji et al., 2001; Kirchmann and Bergstrom, 2001), and irrigation play major roles, along with many other management aspects such as those described by Meisinger and Delgado (2002).

Framework for a nitrate-N leaching index *(NLI)*

The essential framework components of an effective *NLI* index assessment tool are summarized in Table 1. Development of a simple *NLI* index should include the use of appropriate available technology, methods, and databases. These include simulation models and expert systems; databases for soils, climate, and management; use of the Internet (especially client-server methods); and application of Geographic Information System (GIS) technology. The index also needs to allow the input of local site-specific information from producers and field personnel. The index needs to be national in scope and yet flexible enough for use in specialized cases. Use of the index needs to be kept simple and quick with minimal input from the user so that field office personnel can apply the index on a routine basis.

Empirical indices developed using local or regional data can function on a limited basis, but do not provide a general framework for the development of a national index. The complexity of the nitrogen cycle with its many N sources and sinks makes generalization to a unified framework difficult without the use of a mechanistic approach at the process level (Shaffer and Ma, 2001; DeBusk et al., 2001; Shaffer et al., 2001b). Calculation of the process-based *NL* index (eq. 4) is now feasible using any of several available application or research level models (e.g., GPFARM, EPIC, LEACHM, NLEAP, GLEAMS, RZWQM, *ecosys*). For a detailed description of these N simulation models, see Ma and Shaffer (2001).

These models utilize national databases for soils and climate together with regional or local crop and related management databases. In some cases, the models and/or the associated databases are available on-line via the Internet. Results obtained from these models have been validated both nationally and internationally and have been shown to have an accuracy of about 22.4 to 56 kg NO_3-N ha^{-1} yr^{1}, (20 to 50 lb N ac^{-1} yr^{1}) (Shaffer 2002). Use of the *NL* (eq. 4) index as a reliable and known core can provide a sound foundation for a national NO_3-N leaching index (*NLI*).

Given these requirements and available technology, we recommend a 3-tier approach to a new NO_3-N leaching index that provides a uniform method , yet allows for as much refinement of accuracy in the index values as necessary to meet study needs (Fig. 2). Tier 1 would involve the use of an expert system to separate *medium*, *high*, and *very high* nitrate leaching potentials from *low or very low* potential levels by qualitatively screening non-numeric inputs from users. This initial screening technique is approximately parallel to the P index, but would be designed specifically for NO_3-N leaching. The results would not be used for regulation; they would represent only a flagging procedure, indicating if further study was needed. The NO_3-N leaching factors to include in the expert system analysis are summarized in Table 2, and include the basic components: management, soils, climate, and off-site factors. Of these categories, management is the most important and requires special attention. Management has been shown to dominate long-term nitrate-N leaching, regardless of soil or climate effects, which tend to be secondary. Off-site effects may become important on a regional or local basis, but generally remain secondary to management.

Example rankings from the expert system for the upper two levels might be as follows: *high potential for nitrate leaching vulnerability* = irrigated areas; tile drained in the Midwest; manure application (disposal) areas; risky crop

Table 2. Factors important to nitrate leaching index Tier 1 (initial screening, expert system).

Management factors —

- ***General Management***
  - Use of simulation models to evaluate N use efficiencies and total N losses
  - Use of geographic information systems (GIS) to manage variability
- ***Irrigation***
  - Efficiency
  - Scheduling (use of models)
  - Type
  - Water quality (hard water, salts, sodium)
  - Drainage systems (surface or tube)
- ***Cultivation***
  - Minimum tillage
  - Tillage/residue management systems
- ***Fertilizer N***
  - Applied proper N application rate (N budgets)
  - Split N applications
  - Nitrification inhibitors
  - Fertilizer type
  - Method of application
  - Time of application
  - Management zones for N applications
  - Credits for SOM mineralization
  - Credits for residual N management
  - Credit NO_3-N in N in irrigation water
  - In season monitoring of N status (e.g., petiole NO_3-N analysis)
  - Real time monitoring tools (remote sensing, NRI, NDVI)
- ***Manure***
  - N application rates
  - Compost / liquid applications
  - Credits for N and P content
- ***Crop***
  - Shallower versus deeper rooted crop
  - Leguminous versus non-leguminous
  - Rotation (total N uptake, N removed, N recycled)
  - Diseases

Soil factors —

- ***Soil physical and chemical properties***
  - Texture
  - CEC
  - Bulk density
  - Organic matter
  - Drainage
  - Profile depth
  - Coarse fragments
  - pH
  - Phytotoxic ions
  - Water-holding capacity
  - Porosity
  - Preferential flow
  - Slope

Climate factors —

- Temperature
- Rainfall, total precipitation, and distribution
- Probability of having a precipitation event greater than 1, 3, or 12 inches
- Humidity
- Drought periods
- Precipitation timing (significant off season, e.g., winter and spring precipitation)
- Precipitation exceeds ET? (arid, semiarid versus humid)

Off-site factors —

- ***Watersheds***
  - Side of the watershed
  - Use of buffers or other recommended practices
  - Presence or absence of riparian buffer zones
  - Proximity to streams or lakes
  - Karst area

Aquifers

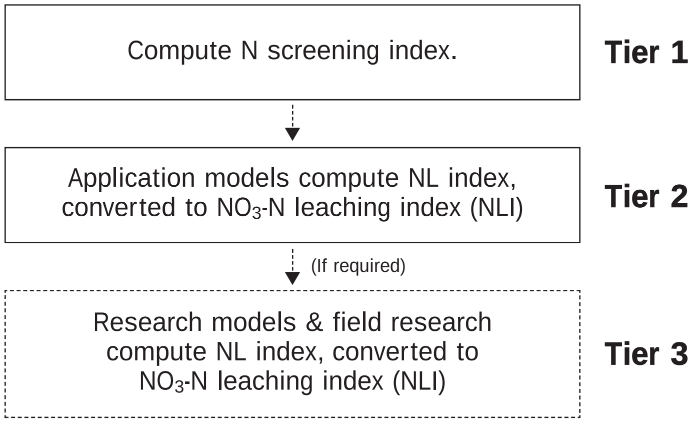
- Depth to water table
- Underlying shallow aquifer (drinking water source) versus deeper confined aquifer

rotations (e.g., shallow rooted vegetable crops); coarse textured soils and high precipitation; shallow drinking water supply; near a lake or stream; karst area. A *high potential* becomes even more critical in combination with sandy soils, a history of high residual nitrates after harvest, fall fertilizer applications, risk for winter/spring leaching from precipitation, or over-application of N fertilizers. Multiple occurrences of potential problems would be justification for a ranking of *very high potential for nitrate leaching vulnerability*. The approach has to be kept simple, but should include the concept that poor management over an extended time period can cause potential NO_3-N leaching problems anywhere, regardless of soils or climate. Soil or climate alone should not trigger concern, especially under good management. Managers might want to customize expert system parameters on a regional or state basis. For example, a local crop rotation or practice might be vulnerable to N leaching, but not commonly used elsewhere.

Tier 2 would provide for routine estimation of a numeric *NL* index using appropriate application level models. Ideally, these models would be accessible from the Internet along with national databases for soils and climate. There are several models available that are tied to regional or national databases and that can make the appropriate *NL* calculations at dynamic steady-state for long-term crop rotations. Examples include NLEAP (Shaffer et al., 1991), GPFARM (Ascough et al., 2001), GLEAMS (Knisel, 1993), and EPIC (Williams and Renard, 1985). The steady-state *NL* results from this calculation could then be normalized to a common range that is tailored to regional or local off-site effects. This would involve the determination of an allowable maximum for *NL* given potential off-site conditions. For example, the presence of a shallow aquifer used for drinking water supplies might require the maximum *NL* be set to 28 kg NO_3-N ha^{-1} yr^{-1} (25 lb NO_3-N ac^{-1} yr^{-1}) to prevent the aquifer from exceeding EPA standards of 10 mg L NO_3-N (10 ppm NO_3-N). If a 0 - 32 range is selected for the *NLI* similar to that selected by Sharpley et al., (2001) for the P index, then the 0 - 28 kg NO_3-N ha^{-1} yr^{-1} range (0 - 25 lb NO_3-N ac^{-1} yr^{-1}) would be normalized to the 0 - 32 *NLI* range. Vulnerability class names could be assigned to ranges within the overall 0 - 32 range, similar to the way they are assigned with the P index (Sharpley et al.,

Figure 2

Tier structure of proposed NO_3-N leaching index (NLI).



1999). A final N leaching index with a common definition would allow comparisons of the index to be made from one region to another where different sensitivities to N leaching may occur.

Tier 3 would provide a case-specific refined estimation of the *NLI* for specific management and conditions using research models and field research. For cases in which a more detailed simulation and / or field study are needed, research models such as RZWQM, LEACHM, or *ecosys*, and research plots or farms can be used to establish refined values for *NLI*. Unusual, difficult, or sensitive situations not handled by the application models would be candidates for the Tier 3 approach. Examples include a fluctuating shallow water table extending into the root zone, wetland conditions such as the growing of rice, and karst geomorphology.

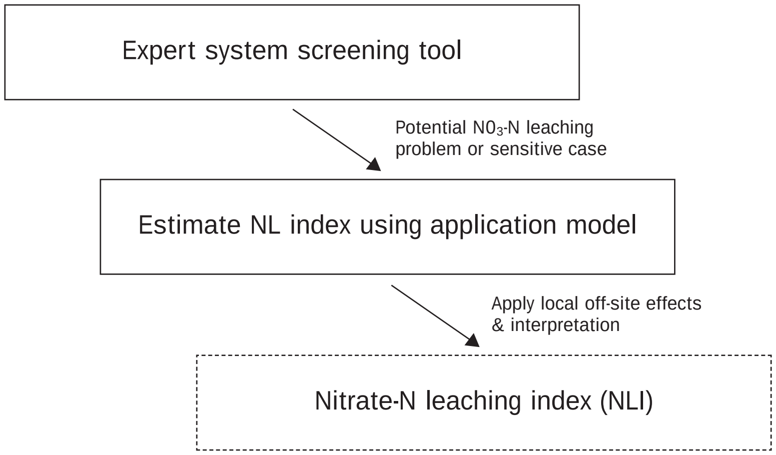
Role of simulation models

Models have several potential roles in the development of the *NLI* index tool, including providing data and information to assist with refinement and extension of the tier 1 expert system. But the most important modeling function would be providing simulation capabilities for calculation of the *NLI* for the second and third tier analyses. This is a critical part of whole process and needs to be done using reliable tools that have been thoroughly tested.

For example, the *MRI* is calculated in the NLEAP versions 1.2 and 1.3. NLEAP incorporates both the *MRI* and *NAL* indices to estimate *NL*. The NLEAP *NL* index has been shown to be correlated with NO_3-N concentrations in shallow underlying aquifers (Wylie et al., 1994; 1995). Some modeling might also be needed to extend the *NL* values to become the *NLI* based on local conditions off-site. For example, associated qualitative interpretation of the *NL* numbers to become *NLI* would depend on local conditions and policies. A good starting rule of thumb for irrigated agriculture over shallow aquifers might be *NL* > 56 kg NO_3-N ha^{-1} yr^{-1} (50 lb NO_3-N ac^{-1} yr^{-1}) will have a *NLI = potential for moderate* NO_3*-N leaching impact; NL* > 112 kg NO_3-N ha^{-1} yr^{-1} (100 lb NO_3-N ac^{-1} yr^{-1}) will have a *NLI = potential for high* NO_3*-N leaching impact; NL* > 168 kg NO_3-N ha^{-1} yr^{-1} (150 lb NO_3-N ac^{-1} yr^{-1}) will have a *NLI = potential for very high* NO_3*-N leaching impact*. But local conditions off-site, such as close proximity to a karst area or surface stream, would require refinement of these number ranges along with possible normalization to a common scale such as the 0 - 32 range used with the P index.

Figure 3

Overall NO_3-N leaching assessment tool.



Importance of Internet Capabilities

All users of the *NLI* assessment tool need to have access to the same (and latest) expert systems, models, and databases. The best way of accomplishing this is to make use of client-server technology on the Internet. This would provide for consistency in *NLI* results across the country and would greatly simplify maintenance and updating of the computer code and databases. The computer programs and databases would reside on server computers located anywhere in the country and client users could access the *NLI* system from anywhere that a suitable Internet connection is available.

Integrated *NLI* Assessment Tool

Figure 3 shows the completed overall *NLI* assessment tool with expert system screening to identify potential NO_3-N leaching problems or sensitive cases and computation of the *NL* index using application models or research simulations for difficult cases, followed by application of off-site effects and local interpretation to produce the final *NLI*. Benefits of this type of tool include rapid initial screening to identify potential NO_3-N leaching problem areas; rapid simulation analyses or database table look-ups to put numbers on qualitative results from the expert system screening by using on-line models and databases on the Internet; and refined results containing normalized *NLI* values based on local off-site effects.

Since the dynamics and transformations of N and P are different as well as their mechanisms for N and P transport, we need to develop a *NLI* assessment tool that can be used separately but simultaneously with the P Index to improve our assessment and evaluation of potential management alternatives that can contribute to N and P cycling and the conservation of our environment. Application of a *NLI* that has been normalized for a range similar to the P index should help to simplify this process. Management trade-offs may be needed to allow both *NLI* and P index values that are within acceptable ranges.

Summary and Conclusions

This paper recommends the essentials for the development of a NO_3-N leaching assessment tool. The resulting *NLI* should be based on hydrological soil properties and climate, with consideration of management practices and associated crop rotations, and inclusion of off-site effects. Management factors have emerged as being dominant in determining the potential for NO_3-N to leach, especially when long-term impacts are involved. The *NLI* assessment tool should be designed for use separately but in conjunction with the P Index to improve our assessment and evaluation of potential management alternatives that optimize both N and P cycling for environmental protection.

Development of the *NLI* should include the use of simulation models and expert systems; databases for soils, climate, and management; and use of the Internet and GIS technology. A 3-tier approach should be used in order to provide a uniform index, yet allow for as much refinement of accuracy in the index values as necessary. Tier 1 involves the use of an expert system to rapidly do an initial qualitative screening to separate *medium*, *high*, and *very high* nitrate leaching potentials from *low or very low* potential levels based on nonnumeric inputs from users. Tier 2 includes the computation of the *NL* index using application models, followed by introduction of off-site effects and local interpretation and normalization to produce the final *NLI*. In difficult cases, a tier 3 study involving detailed research models and field data would be needed along with the off-site effects, interpretation, and normalization.

The *NLI* calculation system would essentially consist of a refined version of the *ALRP* index approach (Pierce et al., 1991; Shaffer et al., 1991) that would include the addition of a web-based expert system for the initial screening of *medium*, *high*, and *very high* NO_3-N leaching potentials, followed by the calculation of the *NL* index at dynamic steady-state using web-based application models and databases, and a final web-based calculation of a normalized *NLI* based on regional or local criteria and off-site conditions. The NLI should be used in conjunction with the P Index to generate alternative management scenarios that optimize both N and P for maximal economic returns while protecting the environment. Technology, databases, and development tools are already available that could be used to build this *NLI* tool.

References Cited

Ascough, J.C., II, M.J. Shaffer, D.L. Hoag, G.S. McMaster, and L.R. Ahuja. 2001. GPFARM: An integrated decisions support system for sustainable Great Plains Agriculture. Paper presented at the 10th International Soil Conservation Organization Conference (ISCO): Sustaining the Global Farm - Local Action for Land Leadership, Purdue University, West Lafayette, Indiana, May 23-28, 1999.

Barton, L. and L.A. Schipper. 2001. Regulation of nitrous oxide emissions from soils irrigated with dairy farm effluent. Journal of Environmental Quality 30: 1881-1887.

Bauer, T., R. Waskom, and J. Alldredge. 2001. Refining Nitrogen Credits from Irrigation Water. Agronomy Abstracts (CD-ROM). Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Bock, B.R. and G.W. Hergert. 1991. Fertilizer nitrogen management. Chapter 7. Pp. 139-164. In: R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.). Managing Nitrogen for Groundwater Quality and Farm Profitability. Madison, WI, Soil Science Society of America, Inc.

Chichester, F.W. 1977. Effects of increased fertilizer rates on nitrogen content and runoff and percolate from monolith lysimeters. Journal of Environmental Quality 6:211-217.

Dabney, S.M., J.A. Delgado, and D.W. Reeves. 2001. Use of winter cover crops to improve soil and water quality. Journal of Communications in Soil Science and Plant Analysis 7 & 8(32):1221-1250.

DeBusk, W.F., J.R. White, and K.R. Reddy. 2001. Carbon and nitrogen dynamics in wetland soils. Pp. 27-53. In: M.J. Shaffer, L. Ma, and S. Hansen (eds). Modeling Carbon and Nitrogen Dynamics for Soil Management. Boca Raton, FL: CRC Press.

Delgado, J.A. 1998. Sequential NLEAP simulations to examine effect of early and late planted winter cover crops on nitrogen dynamics. Journal of Soil and Water Conservation 53:241-244.

Delgado, J.A. 2001a. Use of simulations for evaluation of best management practices on irrigated cropping systems. Pp.355-381. In: M.J. Shaffer, L. Ma, and S. Hansen (eds.) Modeling Carbon and Nitrogen Dynamics for Soil Management. Boca Raton, FL: Lewis Publishers.

Delgado, J.A., ed. 2001b. Potential use of innovative nutrient management alternatives to increase nutrient use efficiency, reduce losses, and protect soil and water quality. Special Issue of the Journal of Communications in Soil Science and Plant Analysis. New York, NY: Marcel Dekker, Inc.

Delgado, J.A. and R.F. Follett. 2002. Carbon and nutrient cycles. Journal of Soil and Water Conservation (this issue).

Delgado, J.A., A.R. Mosier, R.H. Follett, R.F. Follett, D.G. Westfall, L.K. Klemedtsson, and J. Vermeulen. 1996. Effects of N management on N2O and CH4 fluxes and 15N recovery in an irrigated mountain meadow. Nutrient Cycling in Agroecosystems. 46:127-134.

Delgado, J.A., M. Shaffer, and M.K. Brodahl. 1998a. New NLEAP for shallow and deep rooted rotations. Journal of Soil and Water Conservation 53:338-340.

Delgado, J.A., R.F. Follett, J.L. Sharkoff, M.K. Brodahl, and M.J. Shaffer. 1998b. NLEAP facts about nitrogen management. Journal of Soil and Water Conservation. 53:332-337.

Delgado, J.A., R.R. Riggenbach, R.T. Sparks, M.A. Dillon, L.M. Kawanabe, and R.J. Ristau. 2001. Evaluation of nitrate-nitrogen transport in a potato-barley rotation. Soil Science Society of America Journal 65: 878-883.

Delgado, J.A., R.T. Sparks, R.F. Follett, J.L. Sharkoff, and R.R. Riggenbach. 1999. Use of winter cover crops to conserve soil and water quality in the San Luis Valley of south central Colorado. Pp. 125-142. In: R. Lal (ed.) Soil Quality and Soil Erosion. Boca Raton, FL: CRC Press.

Eghball, B., B.J. Wienhold, J.E. Gilley, and R.A. Eigenberg. 2002. Mineralization of manure nutrients. Journal of Soil and Water Conservation (this issue).

Fletcher, D.A. 1991. A national perspective. Chapter 2. Pp. 9-18. In: R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.). Managing Nitrogen for Groundwater Quality and Farm Profitability. Madison, WI: Soil Science Society of America, Inc.

Follett, J.R. and R.F. Follett. 2001. Utilization and metabolism of nitrogen by humans. Chapter 4. Pp. 65-92. In: R.F. Follett and J.L. Hatfield. Nitrogen in the Environment: Sources, Problems, and Management. Amsterdam, The Netherlands: Elsevier Science B.V.

Follett, R.F. and J.L. Hatfield. 2001. Nitrogen in the Environment: Sources, Problems and Management. Amsterdam, The Netherlands: Elsevier Science B.V.

Follett, R.F. and D.J. Walker. 1989. Ground water quality concerns about nitrogen. Chapter 1. Pp. 1-22. In: R.F. Follett. (ed.) Nitrogen Management and Ground Water Protection. Amsterdam, The Netherlands: Elsevier Science B.V.

Follett, R.F. and J.A. Delgado. 2002. Nitrogen fate and transport in agricultural systems. Journal of Soil and Water Conservation (this issue).

Goolsby, D.A., W.A. Battaglin, G.B. Lawrence, R.S. Artz, B.T. Aulenbach, R.P. Hooper, D.R. Keeney, and G.J. Stensland. 1999. Flux and sources of nutrients in the Mississippi-Atchalfalaya River Basin. Report of Task Group 3 to the White House Committee on Environment and Natural Resources. Hypoxia Group. Federal. Register. 64:23 834-23 835.

Hall, M. 1996. Simulation of nitrates in a regional subsurface system: linking surface management with ground water quality. Ph.D. Dissertation. Colorado State University, Fort Collins, CO. 240 pp.

Hallberg, G.R. 1989. Nitrate in ground water in the United States. Chapter 3. Pp. 35-74. In: R.F. Follett. (ed.) Nitrogen Management and Ground Water Protection. Amsterdam, The Netherlands: Elsevier Science B.V.

Hergert, G. W. 1986. Nitrate leaching through sandy soil as affected by sprinkler irrigation management. Journal of Environmental Quality. 15:272-278.

Jokela, W. 1999. Guidelines for Manure Application and Water Quality. Proceedings of SERA-17 Conference. Minimizing P Losses from Agriculture. Quebec City, July, 1999.

Juergens-Gschwind, S. 1989. Ground water nitrates in other developed countries (Europe) - relationships to land use patterns. Chapter 4. Pp. 75-138. In: R.F. Follett. (ed.) Nitrogen Management and Ground Water Protection. Amsterdam, The Netherlands: Elsevier Science B.V.

Kirchmann, H. and L. Bergstrom. 2001. Do organic farming practices reduce nitrate leaching? Journal of Communications in Soil Science and Plant Analysis. 32:997-1028.

Knisel, W.G. (ed). 1993. GLEAMS, Groundwater Loading Effects of Agricultural Management Systems. Version 2.10. University of Georgia, Coastal Plain Experiment Station, Biological and Agricultural Engineering Department (UGA-CPES-BAED), Publication No. 5. 259 pp.

Kronvang, B., J.P. Jensen, C.C. Hofman, and P. Boers. 2001. Nitrogen transport and fate in European streams, rivers, lakes, and wetlands. Chapter 8. Pp. 183-206. In: R.F. Follett and J.L. Hatfield (eds). Nitrogen in the Environment: Sources, Problems, and Management. Amsterdam, The Netherlands: Elsevier Science B.V.

Madison, R.J. and J.O. Brunett. 1985. Overview of the occurrence of nitrate in ground water of the United States. Pp. 93-105. In: U.S. Geological Survey National Water Summary 1984, USGS Water -Supply, Paper 2275.

Ma, L. and M.J. Shaffer. 2001. Review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. Chapter 4. In: M.J. Shaffer, L. Ma, and S. Hansen (eds.) Modeling Carbon and Nitrogen Dynamics for Soil Management. Boca Raton, FL: CRC Press.

Magiotto, S.R., J.A. Webb, C. Wagner-Riddle, and G.W. Thurtell. 2000. Nitrous and nitrogen oxide emissions from turfgrass receiving different forms of nitrogen fertilizer. Journal of Environmental Quality 29: 621-630.

McCrory, D.F. and P.J. Hobbs. 2001. Additives to reduce ammonia and odor emissions from livestock wastes: a review. Journal of Environmental Quality 30: 345-355.

Meisinger, J. and J.A. Delgado. 2002. Principles for managing N leaching. Journal of Soil and Water Conservation (this issue).

Ni, J., A.J. Heber, T. Lim, C.A. Diehl, R.K. Duggirala, B.L. Haymore, and A.L. Sutton. 2000. Ammonia emission from a large mechanically-ventilated swine building during warm weather. Journal of Environmental Quality 29: 751-758.

Owens, L.B., R.W. Malone, M.J. Shipitalo, W.M. Edwards, and J.V. Bonta. 2000. Lysimeter study of nitrate leaching from a corn-soybean rotation. Journal of Environmental Quality 29(2): 467-474.

Pierce, F.J., M.J. Shaffer, and A.D. Halvorson. 1991. Screening procedure for estimating potentially leachable nitrate-nitrogen below the root zone. Chapter 12. Pp. 259-283. In: R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Madison, WI: Soil Science Society of America, Inc.

Pratt, P.F. 1979. Integration, discussion, and conclusions. Pp. 719-769. In: Final report to the National Science Foundation For Nitrate in Effluents from Irrigated Lands. University of California, Riverside.

Randall, G.W. and D.J. Mulla. 2001. Nitrate in surface waters as influenced by climatic conditions and agricultural practices. Journal of Environmental Quality 30(2):337-344.

Schepers, J. S., G. E. Varvel, and D. G. Watts. 1995. Nitrogen and water management strategies to reduce nitrate leaching under irrigated maize. Journal of Contaminant Hydrology. 20:227-239.

Schilling, K.E. and R.D. Libra. 2000. The relationship of nitrate concentrations in streams to row crop land use in Iowa. Journal of Environmental Quality. 29(6):1846-1851.

Shaffer, M.J. 1997. NLEAP model for predicting nitrogen efficiency in irrigated cropping systems. Pp. 198-204. In: Proceedings of the Western Nutrient Management Conference. Salt Lake City, Utah. March 6-7, 1997.

Shaffer, M.J. 2002. Nitrogen modeling for soil management. Journal of Soil and Water Conservation. 57(6)417-425.

Shaffer, M.J. and L. Ma. 2001. Carbon and nitrogen dynamics in upland soils. Chapter 2. In: M.J. Shaffer, L. Ma, and S. Hansen (eds.) Modeling Carbon and Nitrogen Dynamics for Soil Management. Boca Raton, FL: CRC Press.

Shaffer, M.J., A.D. Halvorson, and F.J. Pierce. 1991. Nitrate leaching and economic analysis package (NLEAP): model description and application. Chapter 13. Pp. 285-322. In: R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Madison, WI: Soil Science Society of America, Inc.

Shaffer, M.J., B.K. Wylie, R.F. Follett, and P.N.S. Bartling. 1994. Using climate/weather data with the NLEAP model to manage soil nitrogen. Agricultural and Forest Meteorology. 69:111-123.

Shaffer, M.J., L. Ma, and S. Hansen. 2001b. Introduction to simulation of carbon and nitrogen dynamics in soils. Chapter 1. Pp.1-10. In: M.J. Shaffer, L. Ma, and S. Hansen (eds.) Modeling Carbon and Nitrogen Dynamics for Soil Management. Boca Raton, FL: CRC Press.

Sharp, R.R. and L.A. Harper. 2002. Nitrous oxide and ammonia fluxes in soybean field irrigated with swine effluent. Journal of Environmental Quality 31: 524-532.

Sharpley, A.N., P. Kleinman, and R. McDowell. 2001. Innovative management of agricultural phosphorous to protect soil and water resources. Journal of Communications in Soil Science and Plant Analysis. 7 & 8(32):1071-1100.

Sharpley, A.N., T. Daniel, T. Sims, J. Lemunyon, R. Stevens, and R. Parry. 1999. Agricultural phosphorus and eutrophication. USDA-ARS, ARS-149. 37 pp.

Shoji, S., J. Delgado, A. Mosier, and Y. Miura. 2001. Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. Journal of Communications in Soil Science and Plant Analysis. 32:1051-1070.

Smika, D. E., D. F. Heermann, H. R. Duke, and A. R. Batchelder. 1977. Nitrate-N percolation through irrigated sandy soil as affected by water management. Agronomy Journal. 69:623-626.

Sogbedji, J.M., H.M. van Es, C.L. Yang, L.D. Geohring, and F.R. Magdoff. 2000. Nitrate leaching and nitrogen budget as affected by maize nitrogen rate and soil type. Journal of Environmental Quality 29: 1813-1820.

Thompson, T. L., and T. A. Doerge. 1996a. Nitrogen and water interactions in subsurface trickle irrigated leaf lettuce I. Plant response. Soil Science Society of America Journal 60:163-168.

Thompson, T. L. and T. A. Doerge. 1996b. Nitrogen and water interactions in subsurface trickle irrigated leaf lettuce II. Agronomic, economic, and environmental outcomes. Soil Science Society America Journal 60:168-173.

U.S. Environmental Protection Agency (USEPA). 1989. Federal Register. 54 FR 22062, 22 May. USEPA Washington, D.C.

van Es, H.M., K.J. Czymmek and Q.M. Ketterings. 2002. Management effects on N leaching and guidelines for an N leaching index in New York. Journal of Soil Water Conservation 57(6):499-504.

Westermann, D.T., G.E. Kleinkopf, and L.K. Porter. 1988. Nitrogen fertilizer efficiencies on potatoes. American Potato Journal. 65:377-386.

Williams, J.R. and D.E. Kissel. 1991. Water percolation: An indicator of nitrogen-leaching potential. Chapter 4. Pp.59-83. In: R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.) Managing Nitrogen for Groundwater Quality and Farm Profitability. Madison, WI: Soil Science Society of America, Inc.

Williams, J.R. and K.G. Renard. 1985. Assessment of soil erosion and crop productivity with process models (EPIC). Chapter 5. Pp. 68-102. In: R.F. Follett and B.A. Stewart (eds.) Soil Erosion and Crop Productivity. Madison, WI: American Society of Agronomy.

Wylie, B.K., M.J. Shaffer, and M.D. Hall. 1995. Regional assessment of NLEAP NO3-N leaching indices. Water Resources Bulletin. 31:399-408.

Wylie, B.K., M.J. Shaffer, M.K. Brodahl, D. Dubois, and D.G. Wagner. 1994. Predicting spatial distributions of nitrate leaching in northeastern Colorado. Journal of Soil and Water Conservation 49:288-293.