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Chapter 17. Nitrogen Management Modeling Techniques: Assessing Cropping Systems/Landscape Combinations

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Chapter 17. Nitrogen Management Modeling Techniques: Assessing Cropping Systems/Landscape Combinations

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Nitrogen use efficiency (NUE) in production agriculture is often low, which results in losses of excess N to groundwater as NO_3-N, to gaseous emissions of NH_3 and N_2O, and to N losses in surface runoff and erosion. Best management practices (BMPs) are needed to improve efficiency levels while maintaining proper nutrition for crops. Field studies designed to investigate potential BMPs are both time consuming and costly, and cannot cover all scenarios. Application of simulation models with N cycling components in conjunction with associated field investigations offers methodology that can help identify BMPs that show promise in increasing NUE, but at reduced cost and time expend. Examples from irrigated agriculture, rainfed agriculture, remote sensing, GIS, site specific agriculture, and precision conservation illustrate cases where models have been successfully used to identify potential BMPs to improve NUE and reduce leaching of NO_3-N. However, credible BMP studies employing simulation tools need to proceed along a well-defined path involving model selection, model adaptation and calibration, sensitivity analyses, data requirements and availability, model application, and model results interpretation and limitations. These models could then be used with geographic information systems (GIS), global positioning systems (GPS), and remote sensing, to evaluate various BMPs, enabling them to assessment of efficient N uses at low costs and time expenditures.

Early and continuing interaction with local producers, consultants, conservationists, and field research programs are essential parts of these BMP modeling studies. These model evaluations can be conducted with GIS to assess the BMPs for high risk landscape scenarios with the potential to identify use of Precision Conservation Practices to increase NUE and reduce N losses. This revised chapter will discuss a new series of techniques that can be utilized to assess cropping/ system, landscape combinations that take into consideration the new advances in research that that have been reported since the publication of the first edition of this chapter by Shaffer and Delgado (2001).

1. INTRODUCTION

Nitrogen N is the most vital nutrient used in agricultural systems and contributes greatly to the economical viability, sustainability, and improvement of cropping systems throughout the world. It is necessary to have an adequate supply of this element in the rooting zone of cropping systems to maintain and increase yields needed to supply the nutritional demands of over six and half billion people and the continuing population growth across the world. Nitrogen has been crucial to sustain increases in agricultural productions; however, NUE is usually reported to be lower than 50% (Newbould, 1989). The mismanagement of N has been known to cause a multitude of global problems. Worldwide NUE for cereal production is reported at approximately 33% which is equivalent to billions of dollars of lost revenue (Raun and Johnson, 1999). NUEs lower than 50% can contribute not only to economic losses across all continents, but when N is transported off-site it can potentially have negative impacts on important natural resources (Milburn et al., 1990; Smith et al., 1990; Follett et al., 1991; McCracken et al., 1994; Owens and Edwards, 1994). Drinking water with NO_3-N concentrations above 10 ppm has been established to be unsafe by the United States Environmental Protection Agency (USEPA, 1989). Those most susceptible to high NO_3-N concentrations are infants under 3 months of age that can be affected by blue baby syndrome (clinical methemoglobinemia) (Follett and Walker, 1989). It is imperative to continue the development, evaluation, and implementation of new management practices that increase N recovery and reduce potential losses to the environment. Excess NH_4-N and NO_3-N in soils have been linked with N_2O greenhouse gas emissions (Mosier et al., 1991; Duxbury et al., 1993). Recently, N cycle models such as NLEAP (Shaffer et al., 1991) and DAYCENT (Parton et al., 1998) have been extended to simulate emissions of N_2O from soils (Xu et al., 1998; Del Grosso et al., 2001). Oxygen hypoxia problems in the Gulf of Mexico have been attributed, in part, to nonpoint NO_3-N sources from agriculture (Antweiler et al., 1996) and to low NUEs.

Nutrient management is a key factor to reduce N losses (Delgado et al., 2001a, b; Meisinger and Delgado, 2002; Shaffer and Delgado, 2002). Delgado and Lemunyon (2006) defined "*Nutrient Management*" as "the science and art directed to link soil, crop, weather and hydrologic factors with cultural, irrigation, soil and water conservation practices to achieve the goals of optimizing NUE, yields, crop quality, and economic returns, while reducing off-site transport of nutrients that may impact the environment." They reported that nutrient managers are responsible for and have the difficult task of integrating large datasets of information to match site specific field soil, crop, climate, hydrologic cycle, and crop management practices with the rate, form, timing, place, and method of N application to maximize NUE and profits while reducing losses to the environment. Shaffer and Delgado (2002) proposed that management is a key factor needed to reduce N losses.

Farmers, consultants, and the developers of public policy need efficient tools to help them identify, prioritize, and learn about how nutrient management practices will affect economic returns and regional environmental quality. The coupling of computer models with GIS techniques can help develop public policy that promotes the improvement of economic, environmental, and social-well being of a specific region. Berry et al. (2003, 2005) presented the concept of Precision Conservation (Figures 1 and 2). Berry et al. (2003) defined the emerging concept of Precision

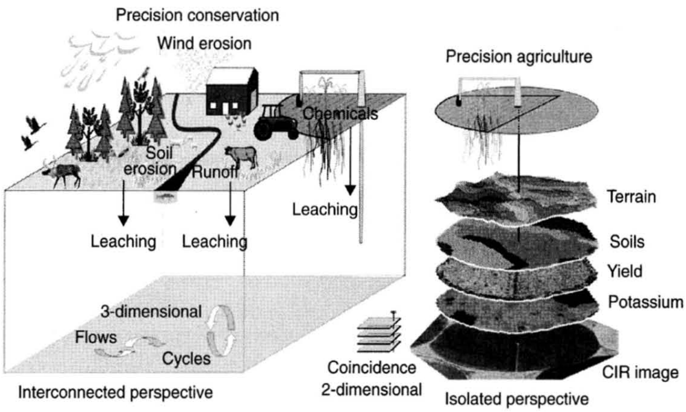

Figure 1. The site specific approach can be expanded to a three dimensional scale approach assessing inflows and outflows from fields to watershed and regional scales. (From Berry et al., 2003).

Conservation as the integration of spatial technologies such as GPS, remote sensing, and GIS and the ability to analyze spatial relationships within and among mapped data by three broad categories of surface modeling, spatial data mining, and map analysis. They recommended that this emerging field of precision conservation and spatial technologies will be used to implement practices that contribute to soil and water conservation in agricultural and natural ecosystems. The new concepts reported by Berry et al. (2003, 2005) are also applicable to N management practices (Delgado and Bausch, 2005; Delgado et al., 2005).

Researchers are constantly working to develop and improve BMPs that increase NUE. Due to the variability of geographical areas, cropping systems, management scenarios, and weather, it is impossible to conduct field plot or whole-farm studies that cover every possible scenario. Computer simulation and decision support (DSS) models for soil-crop systems that emphasize the N cycle, especially when coupled with economics and GIS, are viable alternatives that can contribute to evaluating different combinations of management scenarios and how they impact the recovery of N by a cropping system for a given set of conditions. These models represent complex series of algorithms and databases that can interact with different conditions and serve as mechanistic tools to evaluate different nutrient management scenarios and their effects on NUE, and the sustainability of a system. Shaffer and Delgado

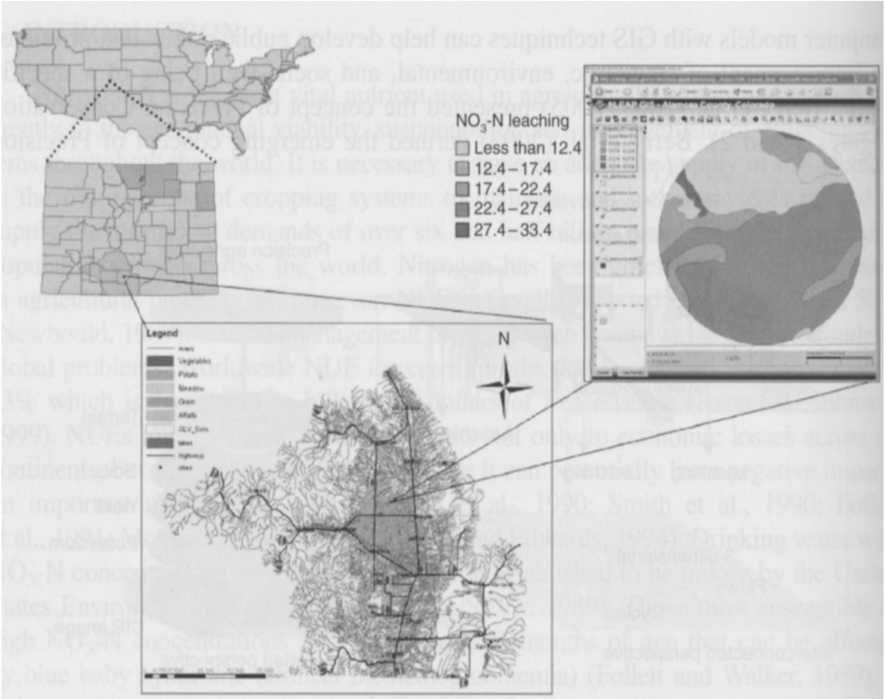

Figure 2. A stand alone NLEAP GIS can be used to evaluate the effects of management practices on N dynamics, transformations of NO$_3$-N leaching across regions. (From Berry et al., 2005).

(2002) recommended a 3-tier approach to assess N management practices. Shaffer and Delgado (2002) reported that Tier 1 would involve the use of an N-Index expert system to quickly indicate the effect of BMPs on N losses. A Tier 2 would involve the use of application models to better assess BMPs. For those more difficult cases, a Tier 3 study involving detailed research models and field data should be used (Figure 3).

System models are, therefore, important tools in the evaluation of how new practices will affect the sustainability and economical viability of agricultural systems and to assess effects of BMPs across cropping systems/landscape combinations across regions. Additionally, models can be used for studies on the effects of management on N dynamics over substantial periods of time. For example, they can simulate the effect of a set of management scenarios and cropping systems such as the incorporation of crop residue versus removal of straw on soil and water quality over a 25–50 year period, or even longer in some instances. Computer algorithms allow the use of large databases that interact with the parameters and management scenarios to identify the best alternatives. These simulation analyses can be used to develop and implement the best management policies that can contribute to maximized economical returns, and improvements in NUE and environmental conservation.

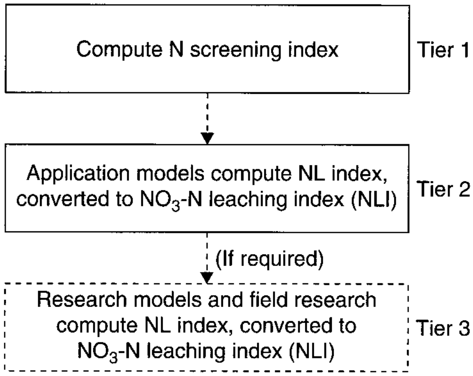

Figure 3. Tier structure of proposed NO_3^--N leaching index (NLI). (From Shaffer and Delgado, 2002).

2. APPLYING MODELS TO FIELD SITUATIONS

Application of models in field studies where conditions are variable and a wide range of potential management scenarios exist can be challenging to agricultural managers and others who need credible, goal oriented, and timely answers. Users of models are quickly faced with a number of issues such as selection of models and databases, collection of model input data in the field, configuring the model for the study, developing management scenarios for the model, installation and operation of the model, model calibration and local validation, and interpretation of the results. Effective and efficient handling of all these model components is necessary if successful modeling results are to be achieved.

2.1. Model Selection

Various agricultural system models are available worldwide with the ability to simulate carbon/nitrogen (C/N) cycling in soil-crop systems. Selection of an appropriate model for a given region and application is not a trivial task and requires knowledge of model capabilities and limitations, as well as the problem and location to be addressed.

C/N models have been applied to a range of environmental and management problems such as NO_3-N leaching, greenhouse gas emissions, carbon sequestration, and soil fertility management to name a few. Detailed descriptions of typical applications involving C/N models can be found in Shaffer et al. (2001b). The amount of detail contained in these models is highly variable and ranges from highly detailed research models to more user-oriented screening tools. Comprehensive reviews and comparisons of these models are presented by Ma and Shaffer (2001) for US models, McGechan et al. (2001), for models in Europe, and Grant (2001) for the Canadian model *ecosys*. The potential user needs to review and judge the model capabilities versus project requirements and select the tool that best fits the user's needs. The best model for a given application usually lies somewhere in the middle near the maximum usability shown in Figure 4. Selecting a model that either is

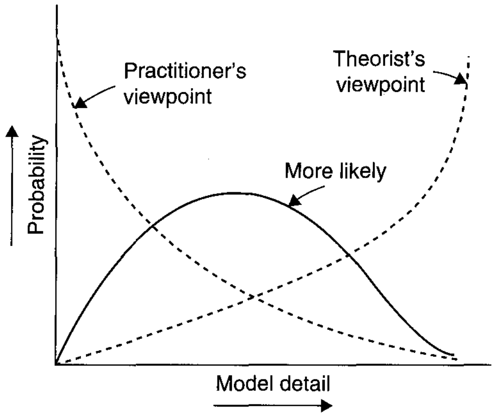

Figure 4. Selecting the best model for a field project. (From Shaffer and Delgado, 2001).

too simple or too detailed for a given application, or that is inappropriate has caused many problems with model application studies in the past and needs to be avoided. Potential model users especially need to look at model capabilities, applicability, reliability, ease of use, data needs, and supplied databases relative to the needs and requirements of their project. For example, if a project contains a specific cropping system, but a model cannot handle this scenario, then that particular model probably cannot be used. Also, if some models do not contain soil and climate databases for the area of interest, then additional work will be needed to develop these resources, and this could play a role in final model selection. If a model was developed and tested in a region with considerably different conditions than the proposed project, then extra effort probably will be needed to configure and calibrate the model for the local area.

Some examples of available models that can be used to simulate C/N dynamics are Crop Estimation through Resource and Environmental Synthesis, CERES (Ritchie et al., 1985); Erosion/Productivity Impact Calculator, EPIC (Williams et al., 1983); Nitrogen Tillage Residue Management Model, NTRM (Shaffer and Larson, 1987); LEACHM (Wagenet and Hutson, 1989); Root Zone Water Quality Model, RZWQM (Ahuja et al., 2000); Nitrate Leaching and Economic Analysis Package, NLEAP (Shaffer et al., 1991); Great Plains Framework for Agricultural Resource Management, GPFARM (Ascough et al., 1998); the University of Minnesota NCSOIL model (Molina et al., 1983); GLEAMS (Knisel, 1993); CENTURY carbon model (Parton and Rasmussen, 1994); the Danish Nitrogen simulation system, DAISY (Hansen et al., 1991); the German model, HERMES (Kersebaum, 1989); the Rothamstead N turnover model, SUNDIAL (Bradbury et al., 1993); the German UFZ model, CANDY (Franko, 1996); the Canadian model, *ecosys* (Grant, 1997); Introductory Carbon Balance Model, ICBM (Andren and Katterer, 1997); the Swedish model, SOILN (Eckersten et al., 1998); and the Dutch model, ANIMO (Groenendijk and Kroes, 1997). Many of these models have internet web-sites that contain model descriptions, and in some cases, the latest versions of the models and their associated databases. An internet search engine such as "GOOGLE" should be used to locate current web-site addresses for these tools.

2.2. Model Adaptation and Calibration

Once a model has been selected, the model must be configured and calibrated to accommodate local, regional areas, and cropping systems. This includes the general layout of the model application, the databases, and the model parameters. The general layout includes items such as the scope of the model options and submodels to use, linkage considerations to other models (e.g., economics packages and GIS), and the types of output variables needed. Databases may need to be customized or extended for local conditions. For example, regional soil and climate databases may not adequately represent local conditions for specific farms. Often, model parameters will need to be determined or refined locally. This may include crop parameters, process rate coefficients, and other functional coefficients. For example, yield and N uptake are NLEAP model functions that can be affected by several parameters. NLEAP uses algorithms that are driven by the expected yield and the N uptake index to simulate the N sink (uptake). Yields can be affected regionally by evapotranspiration, precipitation, temperature (degree/days), and other parameters. Additionally, varieties may change from region to region. There are varieties that have a higher NUE and a lower N uptake index, so the amount of N needed to produce a unit of yield will be lower. Rooting depth parameters can also change with varieties.

The model calibration/validation process should first define the management practices to be evaluated. The effect of soil type needs to be taken into consideration as well as the selection of crops that are grown or that are anticipated to be the dominant crops in the region. For example, the NLEAP "region.idx" model parameter file often needs to be fine-tuned to the local area with additional crops and parameters such as the N uptake indexes. For nutrient management studies involving NUE and NO_3-N leaching, calibration of soil residual NO_3-N should be done by comparing simulated residual soil NO_3-N values with observed NO_3-N values for the root zone and below the root zone. Observed and simulated root-zone, soil water content should be compared and tested in a similar manner.

2.3. Field Setup for Model Calibration

Residual NO_3-N, % soil organic matter (SOM), soil water content, and crop N uptake in commercial fields should be monitored using selected field plots. A good working plot configuration is at least four 20.9 m^2 plots established for replication and size considerations. The plot borders should be identified with field transponders installed at the corners, so the same plots can be re-sampled. Transponders will facilitate the location of the corners within one-inch of variability. New technologies such as real time kinemantic GPS can also be used to identify the border plot with accuracies at the subcentimeter level (Zuydam, 1999). Plot data collected under commercial operations that are monitored more intensively with yield monitors or clipping should be used for the calibration/validation process. Whole field simulations with farmer yields should be used for technology transfer of information (Delgado et al., 2000; Delgado and Bausch, 2005). Farmer yield data from the entire field could be used (truck loads), or if the field is divided by areas, yield monitors or truck loads from the respective areas should be used as inputs for the model.

Above- and below-ground plant samples from different crops, such as small grain and cover crops, are collected by harvesting $0.4\,m^2$. Five plants can be harvested per plot for corn, and four plants can be harvested per plot for vegetables such as potatoes. All above- and below-ground plant compartments need to be sampled. For example, above-ground vines need to be collected for potatoes and tubers harvested. Main roots need to be picked from the plot, especially those for grains including a significant sink, such as the crowns. The mean root depth also needs to be measured for all crops. Plant samples need to be collected prior to harvesting, dried at 55°C, ground, and analyzed for total C and N content. Analyzation procedures include automated combustion using a Carlo Erba automated C/N analyzer©[1]. For the NLEAP model, total N uptake by all compartments needs to be added up and divided by total yield to calculate a mean N uptake index. Water content of the harvested portion needs to be accounted for by collecting a clean fresh weight as soon as the samples have been collected. The water content of the sample then needs to be determined.

One or two soil cores should be taken for the initial and final soil samples collected in each plot. In the case of whole fields, at least 20 cores need to be taken and composited for the initial and final soil samples. If the field is subdivided into areas, each area should then be sampled with up to 20 cores. Soils are sampled in 0.3 m or more frequent intervals down to 1.5 m depending on model needs. Other chemical and physical variables such as the percentage of coarse fragments by weight and by volume, percentage of SOM, pH, CEC, and soil water content are also measured for the initial samples. Soil samples need to be collected from each core and should be kept in cool sealed bags to measure the initial percentage of water content. After harvesting, the same procedure is used for soil samples collected to measure residual soil NO_3-N and soil water content.

The soil samples collected from each 0.3 m (or other) depth increment should be placed immediately into coolers and transported to the laboratory where it is necessary for the samples to be air dried and sieved through a 2 mm sieve. The percentage weight of the coarse fragments is used to calculate the percentage coarse

[1]Names are necessary to report factually on available data, however USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may be suitable.

fragments by volume (Delgado et al., 1998a). Bulk densities need to be determined or estimated from texture as described by USDA-SCS (1988). Soil samples need to be extracted with 2N KCl and the NO_3-N and NH_4-N contents must be determined calorimetrically by an automated flow injection analysis. Records of the irrigation, N fertilizer application, planting, harvesting, cultivation, and other agricultural management practices must be collected to be used as input in the model for calibration purposes. All N inputs, such as amount and type of N fertilizer, amount of N in the irrigation water, crop residue mass and its N content, the initial soil inorganic N content and any other N input required by the system needs to be counted. It is also essential for center-pivot irrigation sprinklers to be calibrated for accuracy, and it is imperative that irrigation water samples be collected at least three times during the growing season and analyzed for NO_3-N. Climatic data needs to be collected at the site or from the nearest weather station. Finally, it is crucial that rain and/or snow amounts are measured locally during the growing season at all sites.

After setups and field calibrations are completed, the models can be used to simulate the effects of crop management on residual soil NO_3-N in the profile and the available soil water in the root zone. The simulated residual NO_3-N for the root zone, bottom of the root zone to the bottom of the soil profile desired, and for the whole soil depth (e.g., 1.5 m) can then be compared to observed values. Correlations between predicted and observed available soil water and between predicted and observed residual soil NO_3-N can then be conducted. For these analyses the intercept (b_0) and slope (b_1) of the regression line can be tested statistically for differences between 0 and 1, respectively.

After the collection of the basic input data and the conclusion of the calibration and validation process on field plots, the model can then be tested for technology transfer on whole field scenarios (Delgado et al., 2000). The simulation of whole field scenarios will model the level of accuracy and variability explained by the simulations (r^2) between measured and simulated values across the whole field. The user must include the potential changes in chemical and physical characteristics across the field due to variability in soil type in the analysis and interpretation. This will aid in accounting for variability in the measured residual soil NO_3-N (variability of x, observed NO_3-N) versus variability due to model simulations (variability of y, predicted NO_3-N) (Delgado, 1999, 2001).

Data collection needed for model calibration/validation and technology transfer efforts should allow completion of the technology transfer process and determination of the effect of BMPs on NUE and transport of NO_3-N in the soil profile. In general, this can require several years and should encompass two or more crop rotation cycles. If the user wants to refine and fine tune the model additionally for more advanced and long-term simulations of N transformations and how these changes may affect NO_3-N leaching, then long-term studies are needed that can evaluate changes in SOM and N cycling. To clarify this scenario, we may need to fine tune and calibrate the simulations of the N pools of the model on longer term scenarios (>10 years) if users want to extend the simulation of these N pools. However, the basic assumptions with calibration/validation and technology transfer processes (6–10 years) have been proven sufficient to simulate the effect of BMPs on NO_3-N dynamics.

Additional crop, soil, and weather inputs are important and need to be accounted for when comparisons are made of BMPs across a region or even across years. Model algorithms have the advantage being used for evaluation of BMPs based on a case by case scenario. An example of why weather data is important is that simulations of BMPs evaluated for a region will be affected by local rain and/or evapotranspiration scenarios, because there may be significant variability of local precipitation and elevation. It is critical that this regional variability is factored into the model. In the case of soil inputs, soil texture could be the same but coarse fragments can significantly vary across a region and can impact the simulations. An example of a crop parameter will be the use of different varieties that can have different rooting depths and N uptake indices.

2.4. Sensitivity Analyses

Sensitivity analysis is important in determining the relative importance of each input, but the analysis needs to be conducted considering long-term scenarios since it could also be confounded by specific initial conditions and events. For example, the interpretation of the sensitivity could be confounded by the initial data used for the respective growing season conditions such as a higher residual soil nitrate content (150 kg NO_3-N/ha) versus a lower initial content (5 kg NO_3-N/ha).

The user can set up a sensitivity analysis to evaluate which model parameters are more important for a region than others. A series of simulations can be conducted by changing one parameter at a time by a factor of 0.25, 0.50, 1.50, and 1.75. This can estimate the relative impact and importance of the input data as well as the impact of the variability of an input parameter. This determines the conclusions affected due to the variability of the input parameters (e.g., results of SOM content from two different laboratories).

2.5. Types of Field Analysis

Application of models to field conditions involves a number of options that must be considered before proceeding with the study. The introduction of GIS technology now allows spatial simulations and mapping to be done across fields, farms, and regions. This capability requires geo-referenced databases to be available for roads, towns, legal boundaries, soils, climate, and management across the study area. Also, the simulation model of interest should be linked with these databases and be capable of providing output back to the GIS software. These linkages can be accomplished using hand techniques, but considerably more time and effort will be required than with an established C/N cycling-GIS interface. Some progress in this area has been made recently using the internet to link C/N model and GIS servers with GIS databases (Shaffer et al., 2001a; Berry et al., 2005; Figure 2). When the required databases and models are available, a GIS analysis of NO_3-N leaching and NUE for an entire farm or region can provide substantially more information and insight than single site analyses. The user must decide whether the additional expense and effort required to conduct a GIS study are justified.

In general, most studies involving projected simulations of NO_3-N leaching and NUE need to be run for multiple years to simulate dynamic steady-state conditions. This allows the effects of the initial conditions to be reduced and to make long-term trends more visible. For example, the effects of an alternate management scenario needs to be evaluated for at least 6–10 years and through at least two crop rotation cycles to allow re-establishment of a dynamic steady-state. Shorter term studies are usually reserved for preliminary model testing and for cases where the period to steady-state is of interest. For example, Delgado (1998) conducted short-term simulations of a lettuce, winter cover crop (WCC) – potato rotation, for a period of 2 years. The study reported that not only do the WCC scavenge the NO_3-N that leached below the rooting systems of the lettuce, but they also reduce the NO_3-N leaching during the potato growing season. We can evaluate the impact and benefits not only during the current growing season, but those that are observed during the growing season of the following crop (Delgado, 1998) or even over two decades due to the effects of changing management practices (Delgado et al., 2005).

Delgado et al. (2005) simulated the long-term effects of site specific management zones (SSMZ) over a 20 year time frame assuming the crop N uptake and organic matter were the same. They assumed that there was no leaching during winter and identical irrigation, background NO_3-N inputs, and weather. Delgado et al. (2005) found that to sustain higher yields in higher productivity zones, these areas needed to receive higher N inputs, which is in agreement with Khosla et al. (2002). Delgado et al. (2005) evaluation suggested that the leaching losses using high N inputs in the high productivity zones were still lower than the zones utilizing traditional farmer practices. The average leaching losses for the high productivity zone of 85 kg NO_3-N/ha with traditional management practices will be reduced to about 25 kg NO_3-N/ha in approximately 7 years with the SSMZ practices. Since there was an average background input of about 60 kg NO_3-N with irrigation water with the implementation these new BMPs, the deeper rooted crop can contribute to mine NO_3-N from the underground water (Delgado et al., 2005; Delgado et al., 2001 a, b; Delgado, 2001).

In addition to GIS applications, C/N cycling models for soils can be linked with applications, such as groundwater models and economics programs. These tools will require specific types of data from a C/N cycling model, such as daily or monthly water and NO_3-N leached and management details usually in the form of a text file or database. If these types of extended applications are going to be used, linkages with potential C/N cycling models should be investigated during the model selection process.

2.5.1. Types of field analysis: Assessments based on field average yield and soil properties

Field techniques to assess N management practices require a setup for model calibration as described in Section 2.3. This field setup will allow the measurement of NUE for each crop-system to be evaluated. Each system NUE can be calculated as follows: NUE_{sys} = ((total N uptake by crop/total N available in the soil profile, e.g., 0–1.5 m) × 100). Total N available includes initial NO_3-N in the soil profile, added fertilizer, added fertilizer in irrigation, background N in water, and simulated N cycling from soil and crop residue mineralized N (Delgado, 1998, 2001; Delgado et al., 2001a).

Another analysis for well irrigated systems is the net NO_3-N recovery from underground irrigation water. This net recovery from underground water will represent the potential for mining NO_3-N by this system (Delgado, 2001; Delgado et al., 2001a). This NO_3-N mining potential is calculated as follows: (a) NO_3-N mining for the root zone equals NO_3^--N in the groundwater added as irrigation water to the field minus NO_3-N leached from the root zone; and (b) NO_3-N mining for the soil profile equals NO_3-N in the groundwater added as irrigation water to the field minus NO_3-N leached from a similar soil profile for the rotation. A large negative number will represent a system with a high potential to contribute NO_3-N to the underground water system since we do not know if all the NO_3-N leached from the system will eventually reach the underground water (e.g., some may be lost by denitrification, or may be recovered by a scavenger crop). A high positive number will represent a system that is serving as a scavenger crop for the NO_3-N added as irrigation water. A positive net recovery simulates a mining process for NO_3-N from underground water. We would then be able to calculate the potential for mining NO_3-N for the root zone or for a similar soil depth. For a rotation that includes shallow and deeper rooted crops such as lettuce-winter wheat, a simulation on a similar soil depth is important, since deeper rooted systems can serve as a scavenger and recover residual soil NO_3-N from below the rooting systems of shallower rooted crops, such as lettuce and potato (Delgado, 1998, 2001; Delgado et al., 1998b, 2001a). The deeper rooted systems of cover crops such as barley, winter wheat, winter rye, sorghum sudan can scavenge residual soil NO_3-N leached from the previous crop, reduced NO_3-N leached from the following crop and served as vertical filter strips capable of mining and recovering NO_3-N from underground water resources (Delgado, 1998; Delgado, 2001; Delgado et al., 2001a, b, 2007).

2.5.2. Types of field analysis: Assessments using GIS and spatial variability of yield and soil

Delgado and Bausch (2005) used GIS and spatial variability of field and soil to determine if productivity zones delineated when precision agriculture technologies were used and if these technologies could identify areas within production fields that differed in residual soil NO_3-N and NO_3-N leaching potential. They conducted these studies with farm cooperators under commercial farm operations. At the field site, the production areas were delineated using the Fleming et al. (1999) productivity zones classification based on soil color from aerial photographs, topography, and the farmer's past management experience (Figure 5).

Delgado and Bausch (2005) collected geo-referenced soil samples in the spring prior to fertilizer applications and after harvest (Figure 5). At harvest, plant samples

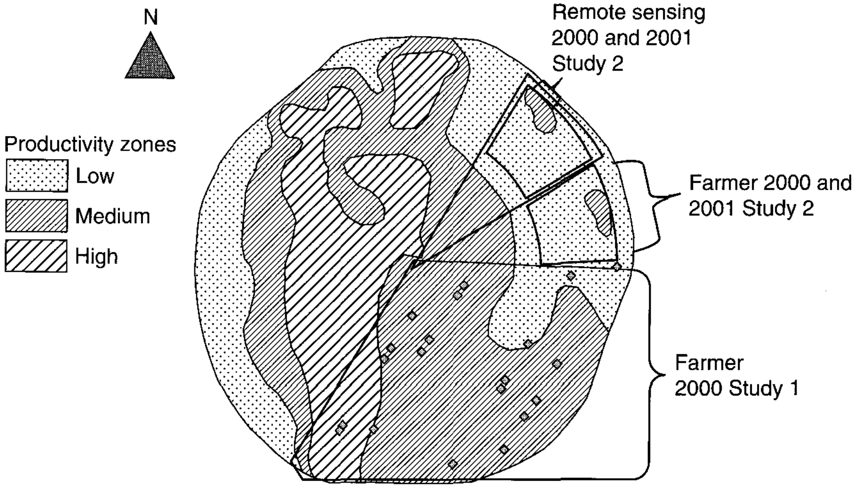

Figure 5. Layout of the random plots monitored in study one across three productivity zones during the 2000 growing season (diamonds). The remote sensing wedge in study two was the location where the N fertigation management "in season" was conducted with the NRI method. The farmer wedge was the similar size truncated area for low productivity zone for farmer's traditional practices. (From Delgado and Bausch, 2005).

were collected and yield was determined from the same locations. Crop planting and harvesting dates, N-, water-, cultural-management inputs and timing, soil and climate information, and other site specific soil properties were entered for each georeferenced position. NLEAP was used to simulate residual soil NO_3-N and NO_3-N leaching. The NLEAP outputs were analyzed using geostatistical methods (kriging) and displayed with maps to identify most risky susceptible areas of the field.

It has been concluded that the combination of NLEAP and GIS is a powerful tool to evaluate the spatial distribution of sand content, residual soil NO_3-N, and NO_3-N leaching variabilities (Figures 6–8). Delgado and Bausch (2005) reported that productivity zones delineated using precision agriculture technologies could identify the areas within production fields that differed in residual soil NO_3-N and NO_3-N leaching potential. Delgado and Bausch (2005) found that the areas with the coarser texture had lower yield, lower residual soil NO_3-N content, and a higher NO_3-N leaching potential. These results from Delgado and Bausch (2005) were in agreement with previous data presented by Delgado (1999), Delgado (2001), and Delgado et al. (2001a) for barley, canola, lettuce (*Lactuca sativa* L.) and potato that found similar responses of lower residual soil NO_3-N and higher NO_3-N leaching in the coarser soil areas.

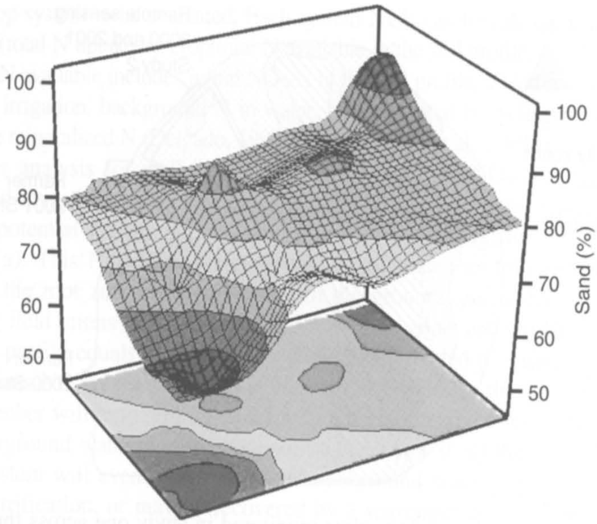

Figure 6. Spatial distribution of sand content in the top 1.5 m of soil for study one across the different productivity zones during the 2000 growing season. (From Delgado and Bausch, 2005).

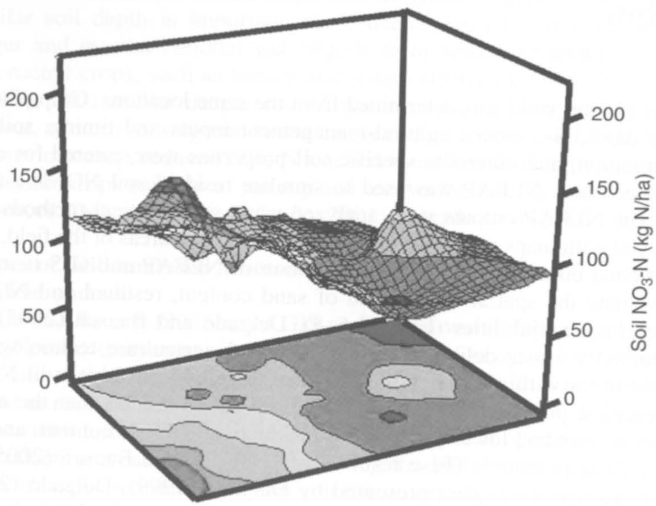

Figure 7. Spatial distribution of observed residual soil NO_3-N in the top 1.5 m of soil for study one across the different productivity zones during the 2000 growing season. (From Delgado and Bausch, 2005).

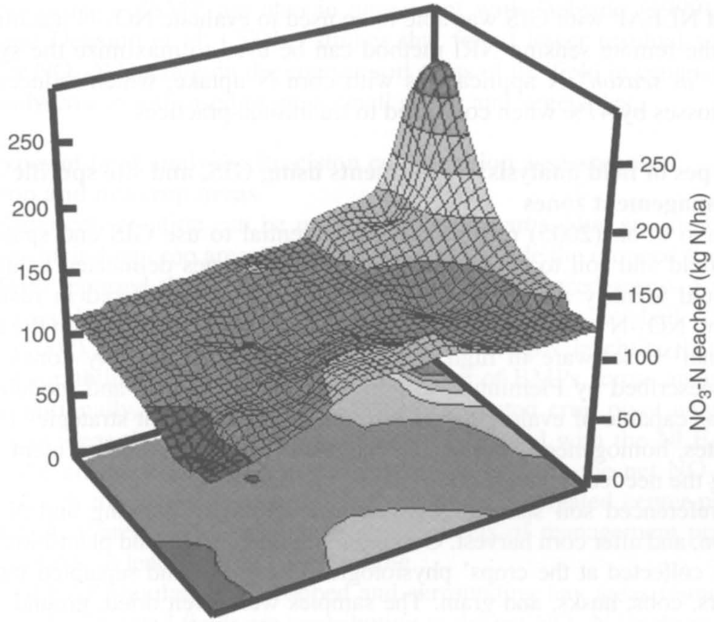

Figure 8. Spatial distribution of predicted NO_3-N leaching from the root zone of corn (1.5 m depth) in study one across the different productivity zones during the 2000 growing season. (From Delgado and Bausch, 2005).

2.5.3. Types of field analysis: Assessments using GIS, remote sensing with site specific yield and soil properties

Delgado and Bausch (2005) used GIS, GPS, yield monitors, and models to assess the potential of using in-season remote sensing measurements to increase NUE and reduce NO_3-N leaching losses. They conducted these studies under commercial farm operations with farmer cooperation during 2000 and 2001 farming seasons. To control the application of N management practices with remote sensing they used a wedge shaped area that received an "as needed" N input, which was determined with remote sensing techniques and crop location (Figure 5). The wedge area was truncated to represent only 3.2 ha located in the low productivity zone as described by Fleming et al. (1999). A similar 3.2 ha area, maintained under farmer's traditional practices was located with GPS in the field, adjacent to the remote sensing area (Figure 5). The "*in season*" N application in the remote sensing area was based on the Nitrogen Reflectance Index (Bausch and Delgado, 2003; Delgado and Bausch, 2005). For a detailed analysis on the remote sensing system, refer to Bausch and Delgado (2003, 2005), Schleicher et al. (2003), and Delgado and Bausch (2005).

These remote sensing techniques allowed quick processing of the canopy reflectance to develop accurate GIS N status and N application maps in comparison to the traditional farmer N management practices. Delgado and Bausch (2005) found that NLEAP with GIS was able to be used to evaluate NO_3-N leaching losses and that the remote sensing NRI method can be used to maximize the synchronization of "*in season*" N applications with corn N uptake, which reduced NO_3-N leaching losses by 47% when compared to traditional practices.

2.5.4. Types of field analysis: Assessments using GIS, and site specific management zones

Delgado et al. (2005) reported on the potential to use GIS and spatial variability of field and soil to determine if productivity zones delineated using SSMZ, which could identify areas within production fields that differed in residual soil NO_3-N and NO_3-N leaching potential. The SSMZ were classified with the AgriTrak Professional™[3] software in high, medium, and low productivity zones with the methods described by Fleming et al. (1999). This GIS, GPS, and modeling study design was capable of evaluating six different N management strategies from variable N rates, homogeneous farmer rates, and site specific N management zones by collecting the needed information to run the NLEAP model.

Geo-referenced soil samples were collected prior to planting and N fertilizer application, and after corn harvest. Geo-referenced, above-ground plant-biomass samples were collected at the crops' physiological maturities and separated into leaves, stems, ears, cobs, husks, and grain. The samples were oven dried, ground, and analyzed for total C and N content by combustion using a Carlo Erba automated C/N analyzer©. For additional information, refer to Delgado et al. (2005).

NLEAP was used to assess the impact of all the N management treatments for each one of the SSMZ on residual soil NO_3-N and NO_3-N leaching. The needed data to run the simulations as described above was entered into NLEAP.

Delgado et al. (2005) found that within N management strategies, NO_3-N leaching is not uniform across the site specific productivity zones. Delgado et al. (2005) reported that NO_3-N leaching is spatially variable across the field with NO_3-N leaching highest in the low productivity zone, while the high productivity zone exhibited the lowest NO_3-N leaching for all N fertilizer treatments. These results concur with Delgado (1999), Delgado (2001), Delgado et al. (2001b), and Delgado and Bausch (2005), which characterized the spatial variability of factors that drive NO_3-N leaching for sandy soils. Delgado et al. (2005) reported that productivity zone is an important spatial factor in determining NO_3-N leaching potential. They reported that a more effective N management practice is to apply the N needed accounting for realistic maximum yields in the low productivity zone to avoid over-fertilization, reduce residual soil NO_3-N, and minimize NO_3-N leaching losses. Delgado et al. (2005) reported that for these sandy soils, as the N rate is increased by productivity zone, the rate of NO_3-N leaching losses increased faster for the "*leaky zone*." They found that under a similar management the low productivity zone has a higher rate of leaching, which means it is a "*leaky system*." Delgado et al. (2005) estimated that by using a SSMZ, NO_3-N leaching losses can be cut by 25% during the first year after a SSMZ nutrient management plan is installed.

These results from SSMZ are also in agreement with Delgado (1999), Delgado (2001), and Delgado et al. (2001a) studies that found lower residual soil NO_3-N and higher NO_3-N leaching in the coarser soil areas of the field in center-pivot, irrigated, sandy-coarse soils used to grow small grains and vegetables.

2.5.5. Types of field analysis: Precision conservation assessment of crop and noncrop areas

Precision conservation can be used to assess the areas that are more sensitive to N losses including crop areas or even hay areas outside the cropped fields. Berry et al. (2005) reported that precision conservation can be used across a watershed scale to assess hot spot areas of NO_3-N leaching within the watershed. Shaffer and Delgado (2002) presented the framework to use a NO_3-N leaching that accounts for spatial variability. Figure 9 shows an evaluation of BMPs across an area of this region. Additionally, Figure 9 shows 15 center-irrigated crop pivot area with the nearby grass areas that are used for hay, which was used with the NLEAP model to assess the effect of traditional management practices on the net NO_3-N leaching losses from this delineated region that covered 15 irrigated center-pivots with surrounding hay areas. NLEAP simulated the effects of management practices on NO_3-N available to leach and NO_3-N leaching.

This NLEAP simulation of cropped and surrounding hay areas found that less than half of the irrigated fields are contributing to the net NO_3-N leaching out of the root zone (NL: red circles), while the larger number, the irrigated areas, are mining NO_3-N from underground water (NL: cyan, green, and yellow areas). These areas

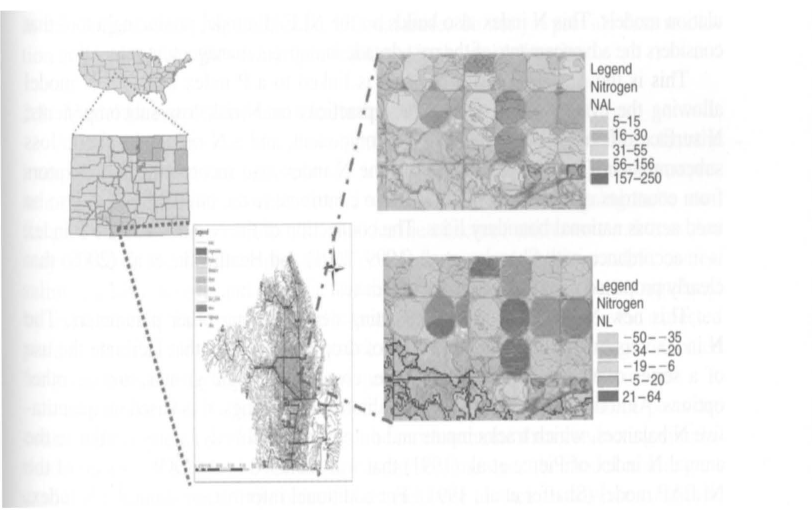

Figure 9. Mass balance for N available to leach and nitrate leaches in an area of a region.

that are mining NO_3-N are planted with a deeper rooted system, while the red areas are shallower rooted crops with higher N inputs. The use of deep rooted crops for this region can serve as a filter and mine background NO_3-N from irrigated water, which was similar to the results from Delgado (1998, 2001) and Delgado et al. (2001a, b). The BMPs across this area (1500 ha) estimate that the shallower rooted crops are leaching 18 Mg NO_3-N, while the deeper rooted crops are scavenging and mining 20 Mg NO_3-N. The irrigated hay areas outside the center-pivot are mining 3 Mg NO_3-N for a net balance of 5 Mg NO_3-N mined from the irrigated center-pivot and irrigated hay areas (equivalent to almost half a circle of N inputs for shallower rooted crops). Rotations of deeper rooted crops and location of hay areas around the cropland are precision conservation methods to scavenge and recover NO_3-N from underground water. This kind of analysis can also be done on a regional basis.

2.6. The Tier One and Tier Two Analysis Approach As Part of the Field Assessment

Shaffer and Delgado (2002) reported that there is the potential and need to develop a new generation N index that can be used to assess BMPs and the potential on N losses. During the past 20 years, various N indexes have been built (Follett et al., 1991; Shaffer and Delgado, 2002; Van Es et al., 2002; Van Es and Delgado, 2006; Wu et al., 2005), but there is still the need for a new N index. Delgado et al. (2006) developed a new second generation N Index. The Delgado et al. (2006) N index was called a new index for three reasons: (1) expanded/combined information, (2) international input, and (3) the ease of use while connecting to P indexes and simulation models. This N index also builds on the NLEAP model producing a tool that considers the advancements of the past decade in nutrient management research.

This is the first time that a N index is linked to a P index and to a N model allowing the evaluation of management practices on N risk loss subcomponents; N surface offsite transport risk loss subcomponent, and a N risk atmospheric loss subcomponent (Delgado et al., 2006). The N index also incorporated cooperators from countries outside the United States to contribute to the building of a tool to be used across national boundary lines. The connection of the N index and the P index is in accordance with Sharpley et al. (1999, 2001) and Heathwaite et al. (2000) that clearly proposed the need to join these indexes.

This new N index accounts for rooting depths among other parameters. The N index version 1.1 has a large number of drop-down menus that facilitate the use of a series of scenarios, such as N type, crops, hydrologic groups, among other options. Although the new N index is qualitative in rankings, it is based on quantitative N balances, which tracks inputs and outputs and soil N dynamics similar to the annual N index of Pierce et al. (1991) that was included in the DOS version of the NLEAP model (Shaffer et al., 1991). For additional information about the N index, refer to Delgado et al. (2006). We suggest that the N index can be used as a tier one analysis followed by a tier two NLEAP analysis if needed (Figure 3). In cases of complex scenarios a more complex model or field study can be conducted (Shaffer and Delgado, 2002). We propose that managers can use the N and P indexes jointly. If required, NLEAP can be used in a tier two analysis.

2.7. Data Requirements and Availability

In general, plot studies for model calibration and validation have shown that local inputs of field data have improved model predictability of residual NO_3^--N, NUE, and NO_3^--N leaching. However, the large areas involved with whole-farms and regions have made data collection at field plot intensities unfeasible from the standpoint of cost and logistics of time and personnel. The question now arises as to how much use can be made of large-scale soil and climate databases without undesirable losses in model accuracy. An even more fundamental question is how accurate do simulation results need to be on a whole-farm or regional scale to allow management decisions at these scales? Issues of up-scaling models developed and tested at smaller (field plot) scales arise here as well. Definitive answers to these questions are beyond the scope of this chapter, but we do know the accuracy of levels being achieved by C/N cycling models for a wide range of field plot studies around the World (Shaffer et al., 2001b).

To maintain this accuracy, input data needs to be provided at the same resolution and detail. Fortunately, recent advances in remote sensing and GPS technology have improved the chances of developing higher resolution soil and climate datasets over large areas. Faster computers coupled with GIS and database technology is now making detailed simulations of regional areas more feasible. Also, georeferenced climate and GIS soil databases are becoming available at a national scale in the United States. Although these GIS databases do not yet provide data resolution at the plot scale, they are a significant step in the right direction.

2.8. Model Interpretation and Limitations

Model limitations need to be accounted for and understood to ensure that the interpretation of the simulated outputs are correct and the conclusions are representative of the dynamics of the natural systems. If the model is going to be used for prediction, the user will have to consider the effects of unknown conditions that may affect yields. For example, the effect of diseases, micronutrient deficiencies, salinity, acidity, weeds, and other factors that may affect yield may not be simulated by some models. The user will need to account for such factors when the expected yield is entered or simulated, or to realize that the simulations are being conducted for average expected yields under the respective BMP simulation scenario.

Using most models for prediction of scenarios under BMPs where pests are controlled and yields are maximized will be more accurate than conducting simulations under weed infestation or with disease problems, since the model or user generally will have to predict the reduction in yield due to such an adverse condition. Additionally, the model may not account for the N uptake by the weeds. Usually the model is being used under BMPs that supply the necessary fertilizer inputs and control weeds, diseases, and pest problems. If other adverse conditions need to be simulated, N partition and uptake by weeds will need to be accounted for, as well as the effects on reduction of yields.

Additionally, crop N deficiency is not well simulated in some models, since models do not reduce the rate of growth at the inflection point where N deficit appears. The user should understand that this type of model is better applied under best maximum conditions, but that it could also be applied to N deficiency conditions. For example, if leaching events are higher than expected due to extraordinary rain events that may impact yields, the user will need to interpret the effect of this N loss and the potential reduction on yield and N uptake. The NO_3^--N leaching under such N deficiencies may be underestimated, since the model will keep assuming the same rate of uptake for the crop. This first simulation could then be followed by a second simulation with a lower expected yield to account for the lower yield and expected lower N uptake. However, by shifting the rate of uptake to a lower curve, the N uptake to the point of high precipitation may then be underestimated, and the NO_3^--N leaching may be overestimated.

Some models may underestimate the expected N uptake for crops and/or varieties that can exhibit exuberant or succulent N uptake. For example, NLEAP uses the expected yield and a mean N uptake index based on total units of N uptake per unit of yield. The N uptake indices were developed under BMPs for commercial operations. Under extremely high N applications, succulent N uptake may be higher than under BMPs, and therefore may be underestimated.

There are climate limitations when some models are applied with certain regions. If using GIS for simulations of BMPs over a particular region, it is important to consider, for example, that the model may not simulate the changes in temperature with changes in altitude. These changes in temperature can affect the simulation of N dynamics due to mineralization of SOM and crop residue, which decreases with higher altitudes and lower temperatures. For such a condition, the region will have to be divided by ecological or climatic variability and the simulations conducted within each division will better simulate these dramatic changes in temperature or precipitation and evapotranspiration. Regional simulations should also consider that single point simulations will not account for differences in yields due to soil type. This can be achieved by dividing the simulations by soil type where the expected yields, by respective soil type, can be entered as an individual input. Similarly, if specific fields are simulated, it is important to collect local precipitation at the site during the period that the simulation is conducted to fine tune and better account for variability in local precipitation.

Other important limitations to consider when using GIS are the capabilities of N models to simulate, in an event by event basis, the transfer of N and water from grid cell to grid cell across the soil surface and soil profile in the z, x, and y directions. Scientists have used simpler approaches to quickly evaluate the effects of N management practices across field and regions (Hall et al., 2001; Delgado and Bausch, 2005). However, there is potential to use point simulations for specific sites and zones linking the outputs with GIS (Hall et al., 2001; Delgado and Bausch, 2005). For example, we could assess the effects of SSMZ by using average inputs of management zones to simulate N management practices, then using GIS to evaluate the outputs (Delgado et al., 2005). Users of these simpler approaches need to be aware and understand the limitations of the models when assessing each specific cropping system/landscape combination with GIS.

Time interval is another potential limitation that needs to be accounted for. For example, NLEAP conducts it simulations using a daily or event-based time interval, so rapid infiltration events, denitrification, or NH_3 volatilization, effects at intervals shorter than a day can create high N losses and may be underestimated by the model. Spatial variability across the field, such as the occurrence of gravel bars, salinity at the lower spots, and significant differences in soil type, will not be simulated by the model. These spatially variable fields can be divided into soil type regions and/or topographic regions within a field, and NLEAP would more accurately simulate these separate conditions (Delgado, 1999, 2001; Delgado et al., 2001b). Major differences in soil layers within the profile will not be simulated since the NLEAP model uses the soil's physical and chemical characteristics across two (and more recently three) soil layers. The new model 1.20 (Shaffer et al., 1998; Delgado et al., 1998b) can account for rooting depth and desired soil profile depth, and can simulate with up to 0.03 m accuracy. This may help by using a more uniform soil depth within a 1.5 m profile, for example, using a 0.9 m profile for simulations.

It is important that the user understands how the model inputs data and how to use the correct input variables. The user also needs to understand how to calculate the predicted or simulated results and have a basic knowledge of N dynamics and effects of management practices.

Results should be summarized and presented in graphs, tables, and text. The simulation of the transport of NO_3-N in the soil profile is very important and the simulation of soil water content is as well. If the simulated residual soil NO_3-N in the root zone and below the root zone is in correspondence with the observed residual soil NO_3-N and the simulated soil water content in the root zone is also in correspondence with field observations, then model assumptions are sufficient to simulate the effects of BMPs on the dynamics and transport of NO_3-N. These graphs of predicted soil water content and residual soil NO_3-N in the root zone and below the root zone versus the observed need to be presented. The evaluation of cropping sequences as well as different soil types, crops, and varieties are also important and should be part of the presentation of the data, as well as the effects on NUE and on underground irrigation water NO_3-N mining potential (Delgado, 2001; Delgado et al., 2001a).

NLEAP uses local databases to simulate N dynamics and has a leaching index that descriptively specifies sensitive of each specific area. This index for NO_3-N leaching can help identify areas that are susceptible and vulnerable to groundwater contamination. It is imperative that inputs used regard the variability of weather, soil type, yields, evapotranspiration, etc. to yield more accurate readings.

3. EXAMPLES FROM IRRIGATED AGRICULTURE

The capability of NLEAP to simulate NO_3-N dynamics in the South Platte region of Northeastern Colorado and the San Luis Valley (SLV) of South Central Colorado has been studied extensively. The land management of the South Platte alluvial aquifer in Northeastern Colorado is mainly dominated with irrigated agriculture. Both center-pivot sprinkler and furrow irrigation are used for corn, potatoes, onions, sugar beets, beans, alfalfa hay, and a number of other specialty crops. The uplands of the South Platte alluvial aquifers are dominated by dryland agriculture and grazing lands. There are numerous confined animal operations (CAFOs) in this region. The manure from these CAFOs is recycled into adjacent cropland areas after harvest. The results of these simulations for these two regions located in Colorado have been published extensively in the literature (Delgado, 1998, 1999, 2001; Delgado et al., 1998a, b; 2001a; Hall et al., 2001; Shaffer et al., 1995; Wylie et al., 1994).

The SLV is an important agricultural base for the State of Colorado with 90% of the potato, 77% of the spring wheat, 81% of the barley, 32% of the oat and 12% of the hay being produced in the state of Colorado during 1996 (CDA and USDA, 1997). In 1996, Colorado was the fifth highest producer of potato in the United States (USDA, 1997). Therefore, the SLV region is an important potato producer for the United States. Other vegetable crops such as lettuce, carrot, and spinach represent an important and viable production base in the valley, with about 7,000 acres planted with these various crops. Irrigated agriculture for this region is of most importance, since it impacts the economics of most of the residents of the valley (Eddy-Miller, 1993). The SLV, with a mean elevation of 2,348 m and a mean precipitation of 180.3 mm, is a high altitude intermountain desert valley that extends 105 miles long and 20 to 50 miles wide (Edelmann and Buckles, 1984; Hearne and Dewey, 1988).

Austin (1993) reported that irrigation started in the SLV with the earlier Spanish settlers who established the first irrigation system in Colorado to divert water from the Rio Grande. Initially, irrigation was limited prior to 1880, but between 1880 and 1890 an intensive network of canals was constructed increasing the area of furrow irrigation (Hearne and Dewey, 1988). Underground water resources became a more important source with the introduction of the high capacity pumps in the 1950s (Hearne and Dewey, 1988). The efficiency of water use increased significantly during the 1970s with the introduction of sprinkler irrigation systems that contributed to an increased irrigated area under these systems. Well numbers increased from 262 wells in 1973 to over 2000 by 1996. Each center-pivot irrigation system covers, on average, 54.7 ha. Furrow irrigation is also still used extensively across this region.

Although there are a variety of soil types across the SLV, the soil texture of this region is dominated by the sandy textured soils or soils over a coarse textured substratum (USDA-SCS, 1973). Nitrate contamination of local wells in excess of EPA standards has been extensively documented in the literature by USGS (Emery et al., 1973; Edelmann and Buckles, 1984). The USDA established the San Luis Valley Water Quality (SLVWQDP) to evaluate the effects of BMPs for this region. The SLVWQDP, USDA-NRCS, and USDA-ARS worked in cooperation to use the

NLEAP model to evaluate the effect of BMPs across different cropping systems. Commercial operations were monitored extensively over the whole valley on over 25 farms, with over 400 different simulations conducted. A list of BMPs for this region was published by Ristau (1999).

NLEAP model simulations for this region show that inclusion of early planted WCC, after lettuce harvest on a lettuce-potato rotation, for example, significantly increases NUE and decreases NO_3-N leached during the potato growing season (Delgado, 1998). Delgado's (1999) sequential simulation shows how important it is to evaluate the crop rotation on a similar soil depth for all crops and to consider the previous year management practices that can affect NO_3-N leaching in the system. He used the new version of the NLEAP model 1.20 that allowed the simulation of multiple crops with different rooting depths (Delgado, 1998, 2001; Shaffer et al., 1998; Delgado et al., 2000). The WCC planted immediately following lettuce harvest, have enough days with optimal growing temperatures to develop a deep rooting system that can scavenge large amounts of NO_3-N from the soil profile (Delgado et al., 1999). Early planted WCC reduces the amount of NO_3-N potentially available to leach, and lowers the NO_3-N leaching during the potato growing season (Delgado, 1998), and contributed to conservation of soil and water quality (Delgado et al., 1999). Delgado (2001) reported a significant correlation between rooting depth and NUE, NO_3-N leaching and the capacity to recover NO_3^--N from underground water sources for small grains and WCC. When well water is used for irrigation, the WCC and small grains act as filters, scavenging the NO_3-N and reducing the NO_3-N losses from the system.

The NLEAP model was capable of simulating different cropping systems from the SLV (Delgado et al., 1998b; Delgado, 2001). Figure 10 presents a correlation for seven irrigated crops grown in South Central Colorado and two irrigated crops from Northeastern Colorado, which illustrated the observed versus predicted residual soil NO_3-N. NLEAP was capable of simulating the effects of management practices on the soil N dynamics for corn and sugar beets grown in Northeastern Colorado. The residual soil NO_3-N for the whole soil profile (0–0.9 m) was lower for the small grain than for the shallower rooted crops that were grown in the SLV (Delgado, 2001). The model simulated the transport of NO_3-N and NO_3-N leaching below the rooting zone of shallower and deeper rooted crops (Delgado et al., 2000). Delgado (2001) reported that BMPs can potentially contribute to saving millions of dollars by increasing NUE in this region of South Central Colorado and decreasing NO_3-N leaching into underground water. If deeper rooted crops are rotated with the shallower rooted crops and if recommended BMPs for N fertilization and irrigation are implemented, they can potentially remove NO_3-N from irrigation water that is applied to the field.

Delgado and Bausch (2005) and Delgado et al. (2005) reported that NLEAP can be used to assess the effect of spatial variability on residual soil NO_3-N and NO_3-N leaching potential of irrigated systems in Colorado. The areas that were more sensitive to NO_3-N leaching losses were the irrigated, coarser areas of the fields that had a lower yield production. Apparently, these areas were the leaky areas of the field,

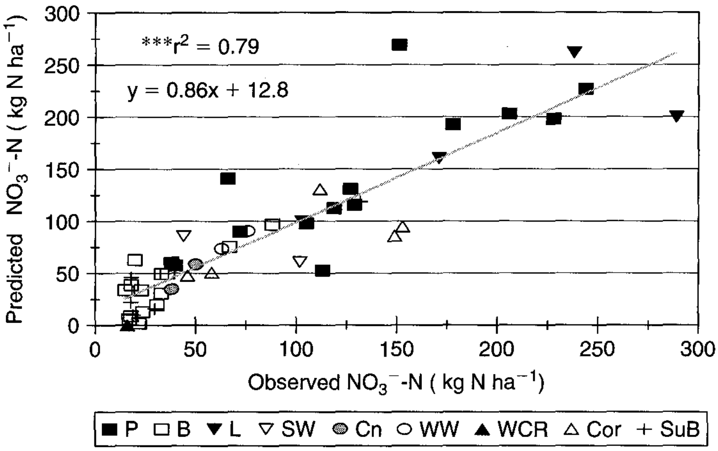

Figure 10. Observed and NLEAP simulated residual soil nitrate (NO_3^--N) in the soil profile. Observed and simulated data for potato (P), barley (B), lettuce (L), spring wheat (SW), canola (Cn), winter wheat (WW), and winter cover rye (WCR) grown in Southcentral Colorado and of corn (Cor) and sugarbeets (SuB) grown in Northeastern Colorado (*** = r^2 significant at $P < 0.001$; From Shaffer and Delgado, 2001).

especially when the whole field needed to be irrigated in accordance with the demand of the higher yielding areas of the field. Delgado et al. (2005) recommended that with a SSMZ approach, it may be better to apply N considering the spatial productivity of the low productive zones and lower N inputs that will use realistic yields for these areas. This will significantly contribute to increase the NUE of the system while reducing losses by 25%. If newly advanced systems that can apply the N demand in synchronization with the N uptake demands by the crop are applied, the N losses can be cut significantly by 45% without reducing yields of commercial applications (Delgado and Bausch, 2005). Modeling tools can be used to assess these management practice effects on NUE, residual soil NO_3-N, and NO_3-N leaching losses, jointly with GIS, GPS, and remote sensing practices on irrigated systems.

4. EXAMPLES FROM RAINFED AGRICULTURE

The NLEAP model has been applied to rainfed agriculture throughout the United States and in foreign countries. Walthall et al. (1996) used the NLEAP model to investigate NO_3-N leaching from fertilizers used in cotton production on the Macon Ridge in Louisiana. Results helped to establish a linkage between NO_3-N concentrations in the shallow groundwater and leaching from the crop root zone in terms of lag times, annual rainfall distribution, and NO_3-N available for leaching.

Kaap et al. (1995) used NLEAP to develop strategies for municipal well-head protection in Central Wisconsin sands. The study involved both rainfed and irrigated areas and found that no simulated NO_3-N leached to groundwater under alfalfa stands, moderate amounts (30–50 kg/ha) leached under rainfed corn and irrigated snap bean, and large amounts (61–130 kg/ha) leached under irrigated corn. The modeling study helped to establish that the use of proposed BMPs alone failed to meet the 10 mg/L NO_3-N groundwater quality standard. Other scenarios were proposed that could help to meet this standard. These alternatives included retirement of agricultural lands to forest or grassland, changing the agricultural crop rotations to more hay, and converting the agricultural lands to residential.

5. EXAMPLES FROM INTERNATIONAL AGRICULTURE

Stoichev et al. (2001), working in Bulgaria, compared NLEAP simulated NO_3-N leaching for sunflower-winter wheat and corn-sunflower-winter wheat rotations with simulated NO_3-N leaching from irrigated home vegetable gardens. The modeling results helped to establish that the majority of the NO_3-N leaching in the local village was from the gardens rather than agricultural fields as initially assumed by the villagers. As a result, remedial measures were recommended to the villagers involving reduced N input to their gardens.

Rimski-Korsakov et al. (2004) used the NLEAP model to assess the causes of groundwater contamination with nitrate in agricultural soils of the Pampas Region, Argentina. They quantified NO_3-N leaching in two fertilized and irrigated soils. The treatments included natural grassland never ploughed or fertilized and irrigated and nonirrigated corn. They found that heavy rainfall in the off season leached high quantities of residual soil NO_3-N. The simulated residual and leached nitrate showed a high correlation with measured values and suggested that NLEAP was appropriate to predict soil nitrate leaching under the studied conditions in the Pampas Region of Argentina.

De Paz (1999) coupled NLEAP to GIS to assess the effects of N management practices in the Mediterranean Region, located in Valencia, Spain, to assess the potential for NO_3-N leaching at a regional scale. De Paz used NLEAP to evaluate vegetable crops such as potato (*Solanum tuberosum* L.), cauliflower (*Brassica oleracea* var. botritys), and onion (*Allium cepa* L.) grown on sandy loam soil. The NLEAP model correlated the simulation of drainage and NO_3-N leaching with measured values. De Paz (1999) found that the vegetable crops such as cauliflower and onion were very susceptible to NO_3-N leaching losses during the initial stage of growth due to irrigation events.

Ersahin (2001) used the NLEAP model to assess the N fertilizer impacts on water quality in Turkey. He studied the effect of spatial variability on NO_3-N leaching parameters in a wheat field. The simulated and measured NO_3-N available to leach was compared. He suggested that this spatial variability in residual soil NO_3-N can be managed with precision farming. This recommendation from Ersahin (2001) is in accordance with the results from Delgado (1999, 2001) and Delgado et al. (2001a). Delgado and Bausch (2005) and Delgado et al. (2005) showed that site specific N management, matching N fertilizer applications to maximum yields across the landscape, reduced NO_3-N leaching. Karaman et al. (2005), located in Turkey, also found that NLEAP was able to simulate the residual soil NO_3-N and NO_3-N leaching. Simulated values were compared to observed values.

6. DISCUSSION AND CONCLUSIONS

Field applications of models for N management are challenging from the standpoint of selecting an appropriate model from the long list of available tools and then applying the model to field situations that often are removed from conditions and locations where the model was developed and tested. The potential user must be prepared to collect a reasonable amount of field data to calibrate the model for the soils, management, and climate conditions in their particular study area. This will involve one or more seasons or years of field work to collect the required crop yield, soil N, and soil water data that is needed. Once this is accomplished, calibration of the model should be done using a systematic approach based on a prior sensitivity analysis run on the tool. The more sensitive parameters for the study region should be adjusted to improve concordance with field data. Some additional testing should also be done with data not used in the calibration to help develop a reasonable amount of validation experience with the model.

Once the calibration procedure has been completed, the model can be applied to test alternative scenarios involving N management. Potential scenarios should be developed in cooperation with local producers, commodities, and action agency groups. Early buy-in of these organizations is essential for later adoption of the BMPs that are identified. In general, simulated scenarios should be run for a number of years until a dynamic steady-state is achieved in terms of residual nitrate in the soil profile. This provides for a better test of long-term management impacts on the system and minimizes the effects of the initial conditions, which may be uncertain across the region or farm. In some cases, shorter term studies may be needed to test, for example, methods of mitigating problems with existing NO_3-N accumulation in the soil profile. Comparisons among simulations of various management scenarios should be done taking into account the uncertainty in the results obtained from the calibration and validation studies. For most N studies in the field, this means that small differences for simulated residual soil nitrates and nitrate leached will not be statistically meaningful for comparisons of some management scenarios. Larger potential differences should be targeted when selecting management scenarios to be tested, especially if producers are expected to demonstrate positive benefits from the adoption of BMPs. Helping to identify scenarios with substantial potential benefits is one of the better uses for modeling in the N management area.

Examples where field modeling studies have identified significant, possible differences in nitrate leaching potentials for alternate nutrient management include a fertilizer and manure management study reported by Hall et al. (2001) where long-term managing at high rates was shown to be leaching excessive nitrates from the root zone, the leaching study of Kaap et al. (1995) in Wisconsin, the Bulgarian NO_3-N study in the village of Parvomaitsi reported by Stoichev et al. (2001), and the leaching simulation work done in the SLV of Colorado by Delgado (2001). Other recent studies were conducted by De Paz (1999), in the Mediterranean Region of Spain; Rimski-Korsakov (2004) in the Pampas region of Argentina; Ersahin (2001) in Turkey; and new modelling applications of precision conservation by Berry et al. (2005); remote sensing, GIS, and GPS by Delgado and Bausch (2005); and site specific N management zones by Delgado et al. (2005). These studies have demonstrated how the application of a C/N model, such as NLEAP, can make a difference in the recommendations of N management scenarios. Basically, these authors applied the procedures outlined in this chapter to implement and complete successful N modeling studies under field conditions.

Models for N dynamics are tools that can be used to help identify and improve BMPs and to transfer research results to producers, consultants, and extension personnel. There is potential to associate N models with P and N indexes and other types of indexes, such as salinity or production indexes (Delgado et al., 2006). Successful field applications of these tools need to proceed along a well-defined path as outlined in this chapter. This begins with model selection and proceeds through field data collection, initial BMP selection, model adaptation, calibration, testing phases, model application, result presentation, and evaluation phases.

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