# Numerical Modeling to Study the Fate of Nitrogen in Cropping Systems and Best Management Case Studies

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**SUMMARY.** Nitrogen (N) availability for crop uptake is dependent on various factors that influence the transformation of N sources and transport of N forms in soils. The fate and transport of N is site specific.

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Therefore evaluation of N dynamics under each condition is neither practical nor feasible. Simulation models which are adequately calibrated and tested can be used to estimate the fate and transport of N as well as crop responses under different production systems. These evaluations provide some guidelines as how to manage N and water efficiently to maximize the N uptake efficiency and minimize the losses. Thus, they contribute to the development of N and water best management practices. In this chapter, we discuss recent information on experimentally measuring the water and nutrient transport in soils as well as performing estimations using simulation models. The development and application of different simulation models for different production systems have been summarized. Some case studies on nitrogen and water best management practices are also discussed. 

**KEYWORDS.** Best management practices, crop rotations, fertigation, leaching estimation and chemistry model, nitrate leaching and economic analysis package, nitrate leaching index, nitrogen uptake efficiency, optimal nitrogen, rootzone water quality model, simulation models, water balance estimations

## *INTRODUCTION*

### *Importance of Numerical Modeling*

With so many different cropping systems, soils, climates, and regions, it is almost impossible to do research studies at every location. Numerical modeling is essential to evaluate the effects of best irrigation and nitrogen (N) management practices across cropping systems and regions. Simulation models are tools that can be tested, evaluated, and calibrated for a specific region and can integrate the evaluation of soil-crop systems and management practices. These models can be used to evaluate irrigation and N uptake efficiencies, and the N dynamics and transport of nitrate-nitrogen ($NO_3$-N) out of the rooting system. There are several levels of models that can be applied to a specific situation and range. From simple index screening tools, to application process models, to highly detailed research process models. The time scale of the simulation to be used can also vary from daily, weekly, or monthly intervals. Models can be used to conduct simulations during the growing season, whole year, or sequential annual simulation, allowing for the flexibility to conduct a systems approach that permits long term evaluations.

### *Data Requirements and Calibration*

There are several models that have been tested and calibrated for carbon and nitrogen cycling. The internet now serves as a link for model information. Shaffer and Delgado (2001) listed the internet websites for 14 of these models where the information can be found. Users need to consider the level of resolution to use and what model to apply for a specific field situation. Nitrogen and water managers debate between theoretic approaches with detailed information as compared to a more practitioner approach that is interested in probabilities. Most of the time the model chosen will fall in a middle point area between theorist and practitioners (Shaffer and Delgado, 2001). Users need to consider the approach and desired level of temporal and detailed resolution. It is important to consider that for a higher resolution model, a higher level of data input is required. Once managers have selected the desired model to evaluate a set of irrigation and nitrogen BMPs on commercial fields, then there is the need for a calibration/validation step. In order to have a grade of confidence on the model and account for regional variabilities or cropping system variabilities, a calibration/validation of a model for a specific region should be conducted. After this calibration/validation process, the model can be used to assess the effects of BMPs, or to conduct sequential simulations. It is important to conduct sequential simulations based on similar rooting depths for the evaluation of cropping systems on system N uptake efficiencies.

The major models have been validated and calibrated across several cropping systems. It is important to keep in mind the model data requirements, model availability, and model limitations when choosing the model. With the internet and recent developments of GIS, models are being used and incorporated as a recommended Best Management Practices to improve N uptake efficiencies and irrigation management practices.

## *ESTIMATING AND MODELING WATER AND NITRATE LEACHING*

The aim of an efficient irrigation scheduling program is to replenish the water deficit within the root zone while minimizing leaching below this depth (Fares and Alva, 2000b). Excess water leaching below the rooting depth may result in nutrient losses which increase production costs and may adversely impact the environment. Thus, a system that continuously monitors changes in soil water content is necessary in order to optimize irrigation and fertilizer management (Fares and Alva, 2000b).

Groundwater $NO_3$-N levels have been reported to be well correlated with land use practices (Hallberg, 1989; Juergens-Gschwind, 1989; Fletcher, 1991; Wylie et al., 1994; Hall, 1996; Hall et al., 2001). Although it is almost impossible to eliminate $NO_3$-N leaching due to irrigation and precipitation events, leaching losses can be kept to a minimum with Best Management Practices (Smika et al., 1977; Hergert, 1986; Westermann et al., 1988; Schepers et al., 1995; Thompson and Doerge, 1996a; 1996b; Delgado et al., 2001b).

### *Measuring Water Leaching*

Paramasivam et al. (2000b) evaluated redistribution and depletion of soil water in a commercial citrus grove under Florida sandy soil. Irrigation was scheduled based on the tensiometer readings at 15 and 30 cm depth under tree canopy along the dripline. Tensiometer readings at below the rooting depth were used to monitor water front, adjust irrigation duration and calculate daily drainage fluxes below the rootzone during the growing season. Under similar soil and weather conditions but for a young citrus grove, soil water content within and below the rootzone were monitored at a 10-min interval using capacitance probes (Fares and Alva, 1999). The soil water content, rainfall, and irrigation data and soil physical properties were used as input parameters into a mathematical model based on the water mass balance method (Fares and Alva 2000a) to calculate both daily evapotranspiration and drainage losses below the rootzone. Drainage losses below the rootzone for 1996 and 1997 were calculated (Fares and Alva, 1999; Fares and Alva, 2000a). During 1996, daily drainage below the rootzone varied considerably due to large variation in the daily rainfall. High daily drainage values were observed during the first three months of the year as a result of some heavy rainfall events. July and August were comparatively dry with monthly rainfall of 134 and 170 mm, respectively, ranging from 75 to 88 percent of the long term averages. Thus, drainage was less than what can be expected during wetter or average precipitation years. The fall of 1997 was very wet compared to 1996 and long-term rainfall average; thus resulted in considerable drainage losses. Similarly, 1996 had wet January and February months with rainfall more than twice the long-term average. The total drainage was 818 mm and 890 mm for 1996 and 1997, respectively. Over 75 percent of this drainage was as a result of rainfall events during the summer wet season. These drainage values are within the range (625 and 860 mm) reported by Rogers and Bartholic (1976) for citrus under Florida conditions.

### *Measuring Nitrate Leaching*

Leaching can be measured with weighing and non-weighing lysimeters or with zero tension or tension samplers (Magid and Christensen, 1993). Since the soil solution will be at different tensions for the micropores, mesopores, and cracks and macropores, the user needs to consider using non-suction or suction lysimeters and the amount of suction to apply (Magid and Christensen, 1993). Zero tension solutes may be more accurate if the objective is to measure the leaching of solutes. Tension samples can be more useful to study soil biogeochemical processes since they collect samples from the micropores where more chemical and biogeochemical transformations are taking place (Magid and Christensen, 1993). Magid and Christensen (1993) also reported that high leaching events with high $NO_3$-N concentrations can also bias the non suction methods.

Owens et al. (1995) used a weighing lysimeter to study $NO_3$-N and water leaching losses from a corn-soybean (*Glycine max* Merr.). They reported that although the water percolation was the same for the corn-corn and soybean-corn rotations, N leaching loss was decreased by about 25 percent in a corn-soybean rotation by accounting for N cycling from soybean residues. This provides additional evidence that management and proper crediting of available N contribution due to N mineralization from previous crop residue improve NUE and reduce N losses to the environment. Computer simulation models are another method to conduct N budgets and evaluation of capability of BMPs to increase NUE and reduce N losses (Delgado, 2002).

### *Numerical Modeling of Nitrate Leaching and Water Drainage*

Because of widespread public concern over the impact of N management practices on water resources, there has been an increasing need to develop N management recommendations by extrapolation of limited research results conducted under specific production and environmental condition into wide range of conditions. Physically based numerical models have increased the estimates for future events to a level beyond "best judgment" decisions. Several numerical models that simulate transport of water and chemicals, including N, have been developed, tested and used to simulate field conditions. Decisions needed to give appropriate advice on the amounts and timing of N to be applied to crops depend on a complex interaction of processes which can be represented in mathematical models. Greenwood et al. (1987) developed a dynamic model to represent the response of winter wheat to N fertilizer. This model has been modified to include the growth simulation of 25 vegetables and major arable crops, and N contribution from crop residues. This model was released to the industry in 1994 as a decision support system for growers (Rahn et al. 1996). Further studies on the release of N from crop residues has lead to the development of a new research model, N_ABLE (Greenwood et al., 1996). These models have now been expanded to run over a rotation of crops and are presently being used to evaluate the effects of different soil management strategies on $NO_3^-$leaching from intensive vegetable rotations.

Nitrate and $NH_4^+$ transport through Florida sandy soils were investigated through an extensive field monitoring and numerical modeling using Leaching Estimation and Chemistry Model (LEACHM) (Paramasivam et al., 2002). This study included four rates of N at either 28, 56, 84 or 112 kg N·ha$^{-1}$ (equivalent to one-fourth of the different annual N rates being evaluated for mature citrus trees). Concentrations of $NO_3$-N were measured soil sampled to 2.4 m depth on a weekly interval. Nitrogen concentrations in the entire profile decreased and approached to the background concentrations by about 42 d after application, irrespective of N rates. The results showed rapid downward movement of N with wetting front following water application from the surface layer deeper into the soil profile.

The LEACHM simulations provided estimates of mass balance loss of applied N with increasing N rates. The study revealed that under extremely sandy soils, leaching losses and groundwater contamination of $NO_3$-N are driven by excess water leaching. Managing irrigation practices to supply water only to replenish the water deficit within the rooting depth of the citrus trees and applying N fertilizers in small quantities with frequent applications help to minimize $NO_3^-$ leaching losses. Numerical modeling provides a tool to enhance understanding of N dynamics and fine-tune N and irrigation management practices aimed to minimize potential negative environmental impacts.

Jabro et al. (1993) compared the transport of $NO_3^-$ measured in a Hagerstown silt loam (fine, mixed, mesic, Typic Hapludalf) soil to that predicted by LEACHM (Hutson and Wagenet, 1992) and NCSWAP (Nitrogen, Carbon, Soil, Water And Plant) (Molina and Richards, 1984) models and concluded that these models did not accurately predict $NO_3$-N leaching to a depth of 1.2 m. They concluded that NCSWAP resulted in significant overestimation of the amount of $NO_3^-$ leached from the soil profile due to an inability to simulate macropore flow effects. It was speculated that $NO_3^-$ was stored in the micropore system and that percolating water bypassed this $NO_3^-$. The use of inappropriate water retention function fitted by Campbell's equation (Campbell, 1984) was, in part, contributing to an overestimation of soil water content which subsequently resulted in non-significant differences between LEACHM simulation and measured data of $NO_3^-$ leaching in the profile. Jabro et al. (1993) further concluded that simulation of $NO_3^-$ leaching by LEACHM was much closer to the measured concentrations as compared to that by the NCSWAP model. Paramasivam et al. (2000a) reported a good agreement between the measured concentrations and those predicted using the LEACHM simulations of $NH_4$-N and $NO_3$-N in a 270 cm depth soil profile following a heavy loading of $NH_4NO_3$ liquid to an uncropped Entisol (Candler fine sand). Soulsby and Reynolds (1992) used LEACHM to model the soil water flux in an aluminum (Al) leaching study. They calibrated the model using in-situ tensiometer data, then compared model predictions against measured tensiometer data for the remainder of the year and found a good agreement.

### *Use of Nitrate-Nitrogen Screening Tools and Application Process Models*

The choice of a model in a given situation is dependent on the expected outcome and deliverables. Shaffer (2002) classified and defined the current N simulation models according to their complexity: i.e., (1) simple index screening tools; (2) application process models; (3) detailed research process models and; (4) highly detailed research process models. The index screening N model tools were defined as models used for a quick qualitative or semi-quantitative evaluation of N management effects. The application process models are those that can provide quantitative estimates of environmental impact of N and are also useful in farm management planning studies, policy option analyses and real time modeling. The detailed research models have more complex C-N interactions and their best applications are oriented to research.

The highly detailed research models are only used in research analyses of soil/crop processes.

Khakural and Robert (1993) and Beckie et al. (1994) found that these screening tools and application models have been found to perform similarly to numerical models in simulating residual soil $NO_3$-N, water content in the rooting zone, and $NO_3$-N leaching. They found that NLEAP performed similarly to the Crop Estimation through Resource and Environment Synthesis (CERES, Ritchie et al., 1986), the Erosion/Productivity Impact Calculator (EPIC, Williams, 1982), the Nitrogen Tillage Residue Management (Shaffer and Larson, 1987), and LEACHM-N, (Wagenet and Hutson, 1989). These simulation models are technology transfer tools capable of assessing the impacts of BMPs on NUE and residual soil $NO_3$-N (RSN) that is available to leach. One of such models is the Nitrate Leaching and Economic Analysis Package (NLEAP) that enables a rapid, site-specific evaluation of BMPs at commercial farmer's field (Delgado, 2001b). The NLEAP simulation model is a technology transfer tool capable of assessing the impacts of BMPs on NUE and residual soil $NO_3$-N (RSN) that is available to leach for irrigated lettuce, potato, barley, canola, spring wheat, winter wheat, and winter cover crops (Delgado, 2001b). Ristau (1999) recommended the use of NLEAP as a best management practice that can be applied to commercial applications for N and water management.

Shaffer (2002) categorized various models into the four subclasses described above. Accordingly, the leaching index model (Williams and Kissel, 1991), the simple option of NLEAP (Shaffer et al., 1991), SUNDIAL (Bradbury et al., 1993) and the Colorado N leaching index (Ceplecha, 2001) were classified under simple index screening tools. The examples for the application process models were: EPIC (Williams and Renard, 1985), CERES (Ritchie et al., 1986), NLEAP (Shaffer et al., 1991), GLEAMS (Knisel, 1993), ANIMO (Groenendijk and Krowes, 1997), CANDY (Franko, 1996), HERMES (Kersebaum, 1995), and GPFARM (Ascough et al., 2001). Examples of detailed research process models were NCSOIL (Molina et al., 1983), SOILN (Johnsson et al., 1987), NTRM (Shaffer and Larson, 1987), LEACHM (Hutson and Wagenet, 1992); SWATNIT (Vereecken et al., 1991), RZWQM (Shaffer et al., 2000), DAISY (Jensen et al., 2001), and DAYCENT (Del Grosso et al., 2001). One example of the highly detailed research model included the *ecosys* model described by Grant (2001).

Once the model has been selected to evaluate BMPs on commercial fields, it is important to calibrate and validate the model for a given situation (Delgado et al., 2001a, 2001b; Shaffer and Delgado, 2002). A model that can do sequential simulations and account for crops and variety differences is needed to evaluate the whole crop rotation (Delgado et al., 1998a; 1998b; 1998c). It is important to conduct sequential simulations based on similar rooting depths for the whole system to account for variability of plant parameters from shallow and deeper rooted crops (Delgado, 1998; 1999; Delgado et al., 1998a; Delgado, 2001b). It is important to keep in mind the model data requirements, availability of data, and model limitations when selecting a model (Shaffer and Delgado, 2002).

### *Development of a National $NO_3$-N Leaching Index (NLI)*

Shaffer and Delgado (2002) discussed the need to develop a *NLI* assessment tool to help identify potential "hot spots" and susceptible areas. The essential framework components of an effective *NLI* assessment tool were summarized by Shaffer and Delgado (2002). They recommended that *NLI* should be based on hydrological soil properties and climate, and must consider management practices and associated crop rotations, and incorporate off-site effects. The *NLI* should be national in scope and yet flexible enough to allow for local site-specific information. The *NLI* should include use of N simulation models and expert systems; databases for soils, climate, and management; and use of the Internet. Shaffer and Delgado (2001) listed the internet websites for 14 C and N cycling models.

The advantages and disadvantages of the previous work done in developing a $NO_3$-N leaching risk indices were discussed by Shaffer and Delgado (2002). The Williams and Kissel (1991) leaching index (*LI*) uses equation V-1. The movement Risk Index (*MRI*) (Shaffer et al., 1991) uses equation V-2. The Nitrate-N available for leaching index (*NAL*) (Shaffer et al., 1991) uses equation V-3. The Nitrate-N leached index (*NL*) (Shaffer et al., 1991) uses equation V-4. The Annual Leaching Risk Potential index (*ALRP*) (Pierce et al., 1991; Shaffer et al., 1991) uses equation V-5. The Aquifer Risk Index (*ARI*) (Shaffer et al., 1991) uses equation V-6. Other indices that have been used to estimate the $NO_3$-N leaching risk have been the Nitrogen Use Efficiency index (NUEI) index (Bock and Hergert, 1991) and the residual soil $NO_3$-N (RSN) index (Shaffer et al., 1991).

$$(LI)\ \mathrm{SW}_1 = \mathrm{SWO}_1 \exp^{(-\Delta t/\mathrm{TT}_1)} \qquad \text{[V-1]}$$

Where: $SW_l$ and $SWO_l$ are water content at the end and start of time interval t and $TT_l$ is the travel time through $layer_l$.

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

Where: k is the leaching coefficient (unitless); WAL is the water available to leach; $POR_1$ is porosity for the top foot; and $POR_2$ is the porosity for the lower horizon.

$$NAL = N_f + N_p + N_{rsd} + N_n - N_{plt} - N_{det} - N_{oth} \qquad [V-3]$$

Where: $N_f$ = N-fertilizer; $N_p$ = $NO_3$-N from precipitation or irrigation water; $N_{rsd}$ = residual soil profile $NO_3$-N; $N_n$ = $NO_3$-N from nitrification; $N_{plt}$ = plant N uptake; $N_{det}$ = denitrification
$NO_3$-N; and $N_{oth}$ = $NO_3$-N loss to erosion and run off.

$$NL = (NAL)\{1 - EXP[(-k)(WAL)/POR_2]\} \qquad [V-4]$$

Where: This is the NLEAP algorithm for $NO_3$-N Leached (Shaffer et al., 1991). Other models use similar algorithms that are different, but functionally equal to Equation 4.

$$ALRP = f(NLy, TT, PA, VA) \qquad [V-5]$$

Where: $NL_y$ = $NO_3$-N leached from the root zone; TT = travel time to reach the aquifer; PA = the position of the aquifer; and VA = the vulnerability of the aquifer.

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

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

The disadvantages and advantages of these indices were discussed by Shaffer and Delgado (2002). In general the *LI* and *MRI* do not account for N dynamics, inputs, and outputs. The *NAL* does not account for water balances and it is difficult to identify off site factors to use in the *ALRP* and *ARI*. The *NL* is not directly tied to offsite factors that control the fate and transport to aquifers, streams, and lakes. The other indices such as the NUEI cannot correlate or differentiate between gaseous and $NO_3$-N leaching losses. The NUEI is not tied to off-site factors.

Shaffer and Delgado (2002) recommended that the development of a National Nitrate Leaching index should be available on the internet. Needed databases and models also should be available on the internet to provide quick access, and the latest version of the model and databases for every user. Users could access the *NLI* system from anywhere using a suitable Internet connection. It was recommended to implement a 3-tier approach. The first tier is to compute the screening index using expert systems that will separate the index into low, very low, medium, high and very high $NO_3$-N leaching potentials. Tier 2 will provide a *NL* index using application level models and tier 3 will provide a case specific model evaluation using research models and field research. N simulation models are another tool that can be used to conduct N budgets and to evaluate N losses from commercial agricultural systems (Delgado et al., 1998b; Shaffer and Delgado, 2001). N simulations models are powerful tools that have been recommended as BMP for commercial operation (Ristau, 1999). They can be used to identify spatial variability in field and management zones or "hot spots" in fields or across regions (Delgado, 2001a; Hall et al., 2001). Often the application process models will have to be calibrated and validated for specific regions. Sensitivity analyses can be conducted to determine the most sensitive parameters to a specific region, crop scenario, or field specific situation (Shaffer and Delgado, 2002). It can be used to evaluate the plant physiological and morphological parameters that are correlated with the potential for mining $NO_3$-N from underground waters (Delgado, 2002).

## *BEST MANAGEMENT PRACTICES: CASE STUDIES*

### *Perennial Crops: Citrus*

#### *Rationale and Description of the Study*

Groundwater is the source of domestic water for about half of the total U.S. population. The principal aquifers supplying drinking water for urban areas typically underlie agricultural areas. Over 50 percent of all fresh water used in Florida comes from groundwater, and over 90 percent of the public relies on groundwater for drinking. Water quality issues, particularly the contamination of groundwater by agricultural chemicals, including $NO_3^-$, have risen to the top of the agricultural and environmental policy agenda. Protecting this vital resource has become one of the most pressing environmental priorities in Florida as well as other areas of the U.S. Groundwater contamination by $NO_3^-$ is a concern in the commercial production of many crops in some parts of the country including citrus on the deep sandy ridge areas of central Florida, predominantly Entisols. This area has been historically well-suited for citrus production due to ideal soil and climatic conditions for production of high yields of good quality fruits. Drinking water and surficial groundwater monitoring data showed indications of increasing trend of excess $NO_3$-N in groundwater in some parts of citrus producing regions of Florida. A proactive, incentive-based program of developing crop specific BMPs began with the 1994 amendments to the Florida Fertilizer Law. This law authorized Florida Department of Agriculture and Consumer Services (DACS) to develop research based crop specific N-BMPs. A combination of optimal irrigation and N management was considered important to improve N uptake, maintain optimal crop yield and to minimize potential leaching of $NO_3^-$ into groundwater. An improved N management practice can be considered as a BMP only if that practice can be demonstrated, on large farm scale studies, to decrease $NO_3$-N leaching into groundwater without adversely impacting the economics of production.

A replicated small plot study was conducted in a Tavares fine sand (hyperthermic, uncoated Typic Quartzipsamment) in Highlands County under optimal irrigation scheduling to evaluate the effects of a range of N rates, sources, and timing of application on fruit yield and juice quality as well as the soil solution $NO_3$-N monitoring components to estimate the amount of N leached below the rootzone. This soil represents a typical vulnerable soil in the central Florida ridge area. 'Hamlin' orange trees on 'Cleopatra mandarin' rootstock were planted in 1974 at 7.62 m $\times$ 6.57 m spacing with a tree density of 287 trees per hectare. The experiment was initiated in the spring of 1993 and continued for 6 years. Nutritional status of the tree (by leaf analysis), fruit yield, fruit quality, and $NO_3$-N levels in soil solution in unsaturated zone (vadose zone) of the soil within and below the rooting depth were monitored.

Fertilizer treatments during the first 3 years of the study (Phase I) included: (i) water soluble granular (WSG) form at either 112, 168, 224, or 280 kg N/ha per yr; (ii) fertigation (FRT) at the above N rates; (iii) 50:50 proportion using WSG and FRT at the above N rates; (iv) controlled release form (CRF); polymer coated urea at either 56, 112, or 168 kg N/ha per yr rates. During the next 3 years of the study (Phase II), an additional treatment of 336 kg N/ha per yr was included only for WSG source, and 3 N rates of CRF were adjusted to 112, 168, and 224 kg N/ha per yr, and an additional treatment of 280 kg N/ha per yr was also included for this source. The frequencies of fertilizer application were 1, 4, and 15 per year for the CRF, WSG and FRT sources, respectively. A commercial fertilizer broadcast spreader (Conibear Equipment Co., Lakeland, FL), adjusted for single-sided application, was used to apply the WSG and CRF sources. The fertilizer spreader was driven close to the edge of the tree canopy to place most of the fertilizer material under the canopy. The CRF was applied in February to coincide with the timing of the first-split application of WSG. The subsequent three applications of WSG were made in April, May and September of each year. Each application of WSG was immediately followed by a light irrigation to facilitate dissolution of the granular product applied and the dissolved fertilizer to be transported slightly below the ground surface for improved root uptake. The FRT was applied in 15 equal doses, with three, and two applications per month from February through May and two applications each during September and October. Since June through August is a period of high rainfall, no fertilizer was applied to minimize the risk of N leaching. The ratio of N/P/K in the fertilizer blend for all sources was 6.0:1.0:6.1, therefore, P and $K^+$ rates being varied with N rates. To achieve optimal tree growth, fruit production, and fruit quality, the N/K ratio in the fertilizer blend was maintained close to 1:1.

*Irrigation Scheduling and Water Balance Estimation*

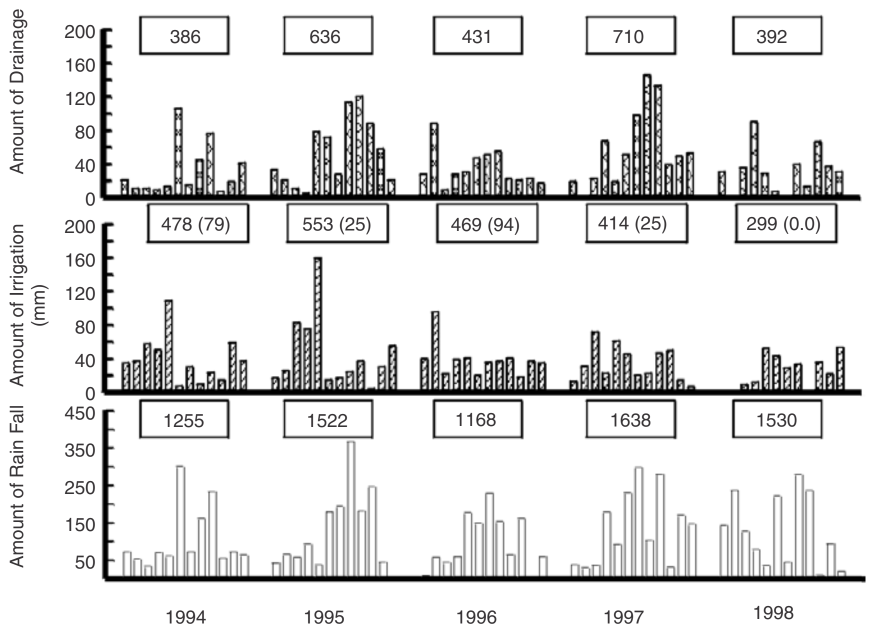
Under the tree micro-irrigation system, with one emitter per tree (delivery rate = 22GPH at $276 \times 10^3$ Pa pressure) was used to wet a circular area of 18.7 $m^2$ per tree (4.9 m diameter), which included most of the ground area under the canopy. Undisturbed soil cores were taken (within the emitter wetting area approximately 30 cm inside the dripline) at 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, 90- to 120-, and 120- to 150 cm depths at five locations within the experiment block to develop a site-specific soil water characteristic curve. This provides quantitative relationship between the gravimetric soil water content and the soil water matric potential. Therefore, the matric potential reading made in the soil using tensiometers can be related to status of soil water content to determine the soil water deficit as basis to schedule irrigation. The field capacity of this soil was the soil moisture content at 8 cbar (Obreza et al., 1997). The gravimetric soil water content at field capacity and permanent wilting point were 6.3 and 1.8 percent, respectively. Thus, the available soil water in this soil was 4.5 percent (field capacity-wilting point). Five clusters of tensiometers, each at the 15-, 30-, 60-, 90-, and 150 cm depths were installed along the dripline of the trees and were read every 2 days. The 15- and 30 cm depth tensiometer readings were used to indicate the soil water depletion level as a basis to schedule irrigation. Trees were irrigated when the 15-, and 30 cm tensiometers read 10 cbar during January through June, or 15 cbar during July through December (Smajstrla et al., 1985). The above set points correspond to 23 and 38 percent depletion of available soil water, respectively. The flowering, fruit set, and initial fruit growth stages (January-June) are critical with respect to the effects of soil water stress, so the allowable soil water depletion was lower during this period than the rest of the year. The duration of the irrigation was calculated using the soil water characteristic curve, emitter delivery rate, the target depth of maximum root activity (90 cm), and irrigation efficiency. Liquid fertilizer was injected to fertigated trees during scheduled irrigation events toward the end of irrigation periods followed by 45- to 60-min rinses of irrigation lines. The WSG and CRF treatments also received irrigation during fertigation. This optimum irrigation practice maintained the crop water requirement only throughout the cropping period. Two rain gauges were installed in the experimental area to record rainfall amounts over the entire duration of the study. Amount of water application at each irrigation was recorded using a flow meter. The monthly cumulative amounts of rainfall and irrigation for each of the five years duration of this experiment are shown in Figure 1.

Cumulative rainfall during the study period ranged from 1170 to 1640 mm which were close to the mean long term annual rainfall for this region, i.e., 1270 to 1575 mm (NOAA, 1996). Although this quantity exceeds citrus tree water requirement, due to the poor distribution of rainfall over the entire year, irrigation is necessary in commercial citrus production to meet production and quality goals.

Drainage (Q) below the rootzone was calculated, assuming steady state water, as the product of Darcy's flux (q) and the time period ($\Delta$t) for which drainage was being calculated. Using measured soil water potentials below the rootzone, 90 cm, and saturated hydraulic conductivities, water fluxes below the rootzone were calculated using Darcy's flux equation, as $Q = q \Delta t$.

Irrigation was well managed throughout the study period with the help of tensiometer, drainage of water occurred beyond the rootzone

FIGURE 1. Monthly summary of water balance (rainfall, irrigation, and drainage) data 1994 through 1998 at the experimental site with 24-yr-old 'Hamlin' orange trees on 'Cleopatra mandarin' rootstock in a Tavares fine sand. Emitter wetting pattern was 48 percent of grove area. Annual totals of each parameter by each year are given in boxes at the top of the histograms. Numbers in parentheses next to the irrigation data indicate amount of irrigation used for freeze protection (mostly in January) during the respective years.

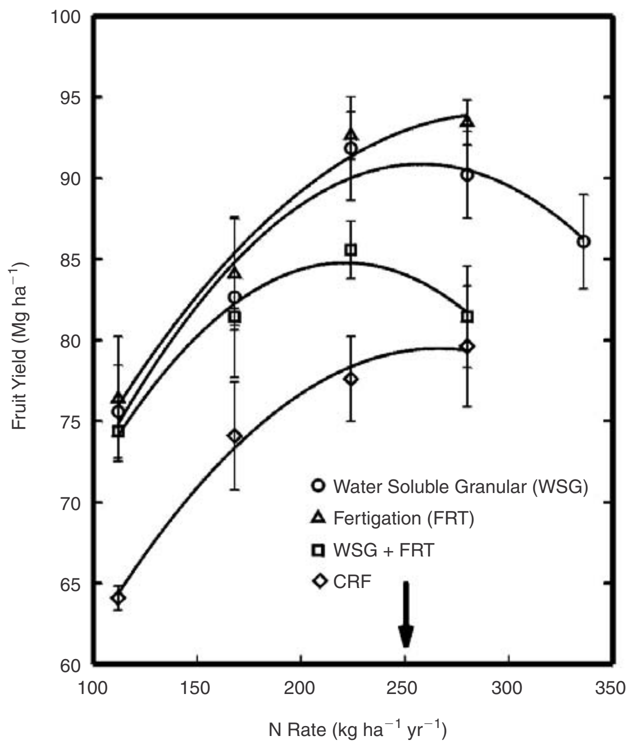



during the rainy period of the year. The amount of drainage water is presented on monthly basis for the 1994 through 1998 study period (Figure 1). Cumulative annual drainage varied from 400 to 730 mm and represented 23 to 33 percent of the total water input for this study period.

### *Fruit Yield Response and Optimal N*

Over the range of N rates from 112 to 336 kg N/ha per yr fruit yield response showed a quadratic relationship (Figure 2). Unfortunately, this study did not include N rates greater than 280 kg N/ha per yr for fertilizer sources other than WSG source. However, the slope of the response curve decreased substantially in the N range for 224 to 280 kg N com-

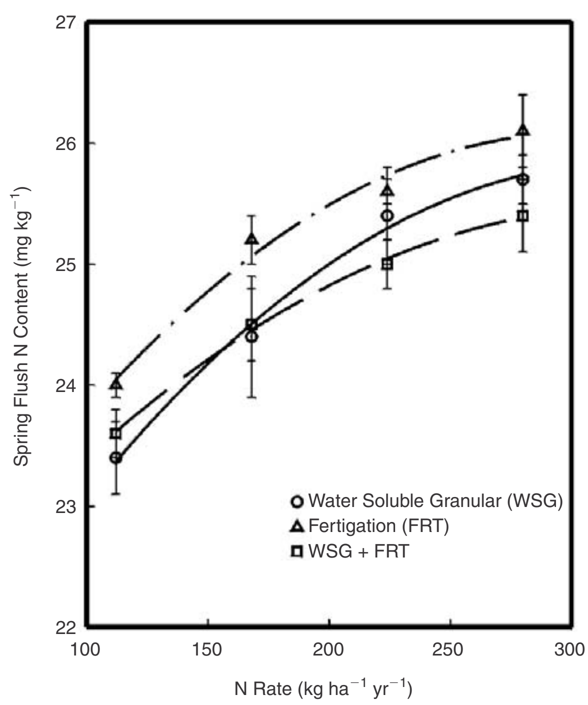
FIGURE 2. Relationship between fruit yields (mean across 4 yr; 1995-98) of 'Hamlin' orange trees on 'Cleopatra mandarin' rootstock planted in a Tavares fine sand, and N rates applied as either water soluble granular fertilizer (WSG), combination of WSG and FRT (at 50:50 ratio), and controlled release fertilizer (CRF) and fertigation (FRT),with optimal irrigation management. Vertical line at each mean value represents the standard error of the mean. An arrow pointing to the X-axis indicates predicted optimum N rate using the response data.




pared to that in the range of 168 to 224 kg N$\cdot$ha$^{-1}$. The fruit yield differences were non-significant between N rates at 224 and 280 kg N/ha per yr for fertigation. For two N source treatments (WSG and WSG + FRT) the fruit yield shows a slight decrease with an increase in N rate from 224 to 280 kg$\cdot$ha$^{-1}$. This is an indication of negative yield response at N rates greater than 280 kg$\cdot$ha$^{-1}$. Based on the statistical analysis of 4-yr yield data (1995-98) the optimum fertilizer N rate under this experimental condition was 258 kg N/ha per yr. During the 6-yr study period, the mean leaf N concentrations were in the low to optimum range. This was affected by both N sources and rates. Mean spring flush N content was within the optimum range (25.0 to 26.2 $mg \cdot kg^{-1}$) for the trees which received $\geq$ 168 kg N/ha per yr as FRT, and at $\geq$ 224 kg N/ha per yr as WSG or 50:50 WSG: FRT treatments (Figure 3).

The orange variety used in this study was 'Hamlin' on 'Cleopatra mandarin' rootstock, a high yielding variety with the state average yield of about 50.4 $Mg \cdot ha^{-1}$. However, the mean yield over 6-yrs in this experiment varied from 68.0 to 85.7 $Mg \cdot ha^{-1}$ with N rates in the range of 112 to 280 kg/ha per yr. Mean fruit yield was low in the range of 52.9 to 63.0 $Mg \cdot ha^{-1}$ only when the N was applied as a controlled-release N

FIGURE 3. Relationship between concentration of N in 6-mo-old spring flush leaves (mean across 4 yr; 1995-98) of 'Hamlin' orange trees on 'Cleopatra mandarin' rootstock planted in a Tavares fine sand, and N rates applied as either water soluble granular fertilizer (WSG), fertigation (FRT), and combination of WSG and FRT at 50:50 ratio with optimal irrigation management. Vertical line at each mean value represents the standard error of the mean.



source. It was estimated that about 5.1 to 5.5 kg N is removed from the crop with every 10 Mg of fruit that was harvested each year. This amount should be adjusted to account for N required for the new annual growth, storage within the plant, and application efficiency. If the supply of N in the form of fertilizer does not meet the crop demand, then N will be transported from plant storage areas and which will in turn result in low leaf N content. Therefore, it is important to apply inorganic and organic fertilizer N to meet the crop demand and maintain a sustainable crop.

### *Estimated Cumulative $NO_3$-N Leaching Losses Below the Rootzone*

The fibrous roots are usually most densely concentrated near the soil surface. The distribution of citrus trees fibrous roots decreases substantially below the 30 cm depth, with very few roots at 120 cm (Castle, 1980). Nitrates in soil solution at the 60 and 120 cm depths, thus, represent the source of N available for root uptake. However, the 240 cm depth of sampling is well below the zone of maximum distribution of fibrous roots. Any $NO_3^-$ detected at this depth is not available to the trees, nor can it be readily transformed due to the limited microbial population at that depth as well as availability of carbon source for the microbes. Therefore, the concentration of $NO_3$-N in the soil solution at the 240 cm depth is an indication of potential leaching of $NO_3$-N into groundwater.

A careful selection of source and rate of fertilizer and careful irrigation management are important to reduce leaching losses (Alva 1992; Alva and Tucker, 1993; Syvertsen and Smith, 1996; Alva and Paramasivam, 1998; and Alva et al., 1998), thereby, to enhance nutrient-uptake efficiency by the crop. Downward movement of soil-applied N depends on the transport of water (Nightingale, 1972; Hallberg, 1989; Hubbard et al., 1984; 1986; 1989). Therefore, it is necessary to optimize irrigation management to minimize leaching of $NO_3$-N below the rootzone. Likewise, choice of appropriate source, amount, timing, frequency of fertilizer application and rate of N transformation into $NO_3^-$ are other important factors that determine the amount of $NO_3^-$ available for leaching. The amount of $NO_3$-N subject to leaching is a function of available $NO_3$-N in the profile and excess water that passes below the rooting depth. Further, fertilizer application was avoided during heavy rainfall months to minimize leaching losses in this study. In addition, in this study, duration of irrigation after fertigation was limited to 45 min, just sufficient to rinse the line and move the applied fertilizer slightly below the soil surface, without causing excessive leaching below the rootzone.

Nitrate leaching losses below the rootzone ($A_N$) were estimated using the concentration of $NO_3$-N in soil solution collected at various sampling events from the suction lysimeter installed at the 240 cm depth in the vadose zone ($C_{SL8}$) and the amount of drainage water at this depth (Q) under the citrus canopy, i.e., $A_N = Q \cdot C_{SL8}$. Summation of these quantities over a period of one year, thus, provide an estimate of total amount of $NO_3$-N leached below the rootzone. Estimated cumulative $NO_3$-N leaching losses for two years for the two high N rates applied as WSG, FRT, and CRF, are presented in Figure 4. During the phase I of this study, the high N rates for CRF source (112 and 168 kg N/ha per yr) were different than those for the WSG and FRT (224, and 280 kg N/ha per yr) sources. The cumulative amounts of $NO_3$-N leached below the rooting depth from WSG source were 14 and 23 kg N/ha per yr for 224 and 280 kg N/ha per yr, respectively, for the 1994 cropping year (Table 1). The corresponding amounts for 1995 were 13.8 and 21.3 kg N/ha per yr. Estimated cumulative leaching losses of $NO_3$-N from FRT source amount to 23.3 and 29.3 kg N/ha per yr for the same N application rates respectively for the 1994 cropping year and these losses were 30.1 and 30.5 kg N/ha per yr for the 1995 cropping year. The cumulative $NO_3$-N leaching losses from the CRF source amounted to 1.1 and 3.2 kg N/ha per yr for the N application rate of 112 and 168 kg N/ha per yr, respectively, for the 1994 and 3.9 and 8.0 kg N/ha per yr, respectively, for the 1995 cropping year.

A study in a large watershed in southern California with citrus reported 67 kg N/ha per yr leaching losses (Bingham et al., 1971). This accounted for 45 percent of the annual applied N. Avinimelech and Raveh (1976) reported average leaching losses of 50.4 and 127.7 kg N/ha per yr for citrus grown in a clay loam and sandy loam soil, respectively, in Israel. Dasberg et al. (1984) reported < 50 kg N/ha per yr leaching loss in a study in Israel with 760 mm irrigation and application of up to 180 kg N/ha per yr. In all of the above cited studies, N leaching was estimated by using the mean $NO_3$-N concentration in subsoil solution and annual amount of water passed through the soil profile. The N leaching quantities estimated in the current study were lower than those reported in the above studies. This lower quantities of N leaching predictions in this study as compared to those reported in the other studies were an indication of an improved management of N and irrigation which contributed to decreased leaching of water as well as $NO_3$-N.

FIGURE 4. Estimated cumulative water drainage, and amount of $NO_3$-N leached for two years below 240 cm depth in a Tavares fine sand with 25+ year old ‘Hamlin’ orange trees on ‘Cleopatra mandarin’ rootstock which received different rates and sources of N (modified from Paramasivam et al., 2001).

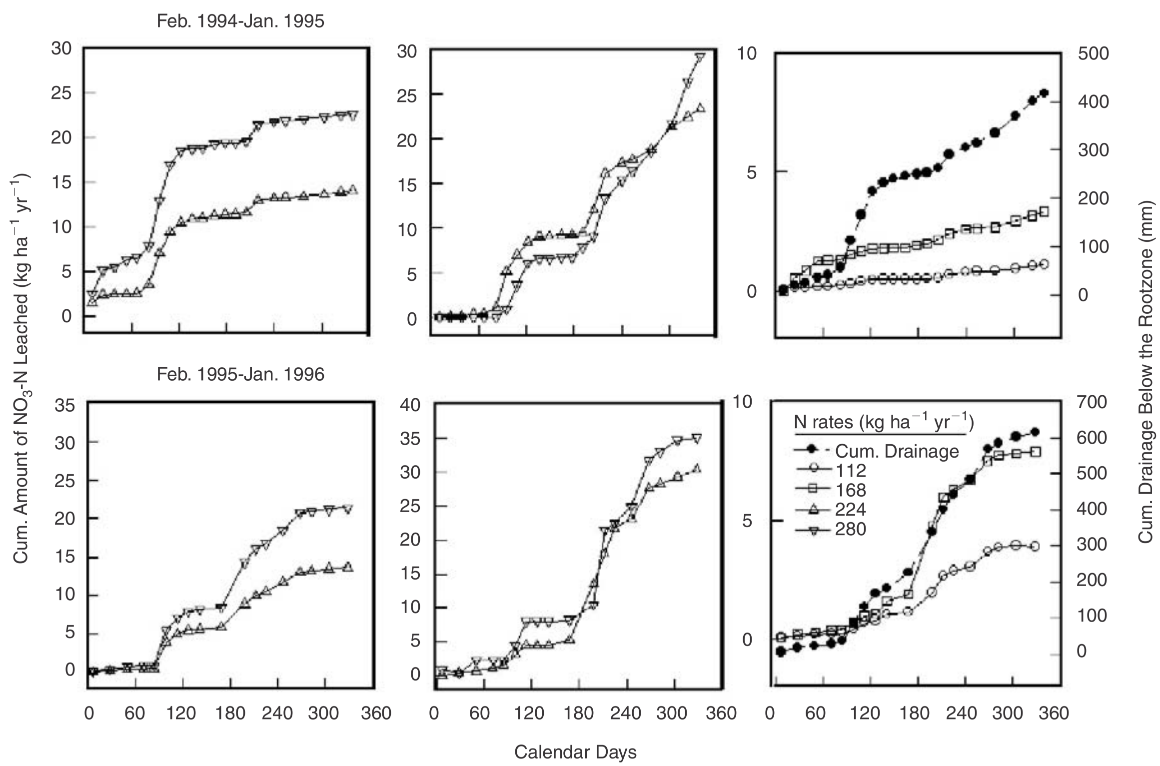


TABLE 1. Calculated cumulative amounts of $NO_3$-N in the soil solution collected at 240 cm depth as an approximate amount of N leached below the rooting depth on an annual basis with application of 224 and 280 kg N/ha per yr as WSG or FRT and 112 and 168 kg N/ha per yr as CRF to 24-yr-old 'Hamlin' orange on 'Cleopatra mandarin' rootstock grown in a Tavares fine sand (modified from Paramasivam et al., 2001).

| Year | WSG | | FRT | | CRF | |
|---|---|---|---|---|---|---|
| | 224 | 280 | 224 | 280 | 112 | 168 |
| | kg N/ha per yr | | | | | |
| 1994 | 14 | 22.6 | 23.3 | 29.3 | 1.1 | 3.2 |
| 1995 | 14.8 | 21.3 | 30.5 | 35.1 | 3.9 | 8 |

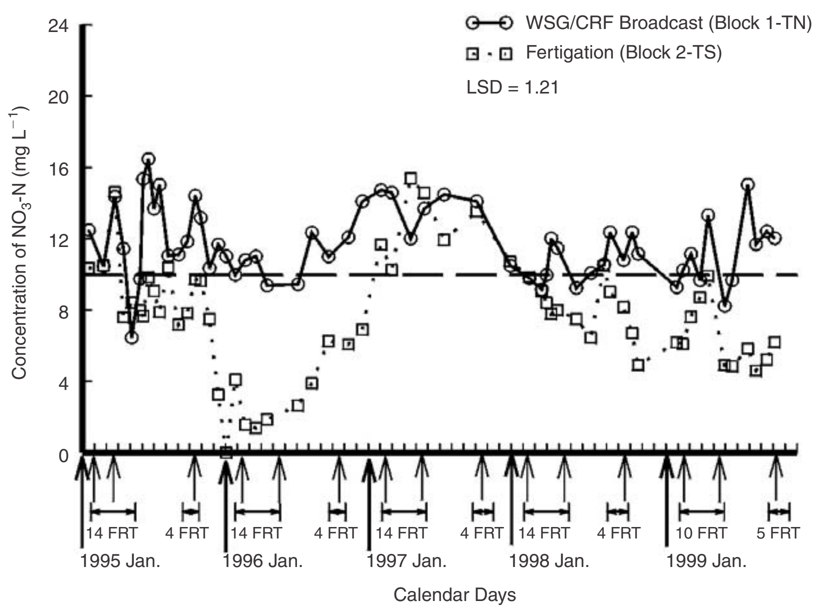
### *Demonstration of N BMP*

The aim of the detailed replicated plot experiment described above was to study the N fate and transport, and fruit yield response to various sources and rates of N. The information gained from this study was used to develop preliminary N BMP, which was further evaluated in a large scale commercial blocks to evaluate the long term effects of the proposed N BMP on fruit yield, quality, tree nutritional status, and finally on the $NO_3$-N concentration in shallow groundwater. Two commercial citrus grove sites (32.4 ha each), largely similar in terms of scion/rootstock combination, percentage annual tree mortality and resets, past fertilization practices, past production records, soil type, elevation, etc., were selected. On the basis of preliminary hydrology investigations, the quality of groundwater within each block was reflective of the practices carried out within the block quite independent of the practices in the adjacent block and/or adjacent commercial groves. The soil type at the trial site was Astatula sand (hyperthermic, uncoated, Typic Quartzipsamments). The grove was planted in 1965 with 'Valencia' orange trees on 'Rough lemon' rootstock, at 286 trees per hectare with approximately 15 to 20 percent resets. One block received 90 kg N/ha per yr as 50:50 mix of water soluble granular (WSG as ammonium nitrate) and controlled release fertilizer (CRF) N sources in late January or early February, followed by two applications of 45 kg·ha$^{-1}$ each as ammonium nitrate during April and September. The CRF used was a polymer-coated sulfur-coated urea with a release duration of 90 d. The ratio of N/P/K in the fertilizer blend used in all three applications was 16.0:8.0:16.0; therefore, P and K rates were also varied along with N rates. To achieve optimal tree growth, fruit production, and fruit quality, the N/K ratio in the fertilizer blend was maintained close to 1:1. The N rate for Block 1 was increased to 210 kg/ha per yr effective 1998 fall and from 1999 all of the N was applied as only WSG form in four split applications per year. The Block 2 received 180 kg N/ha per yr in 18 applications as fertigation. As of 1999, the number of fertigations for Block 2 was reduced to 15. A N:P:K solution containing a nutrient ratio of 6:4:8 was used during January and February (6 doses) and a solution with slightly different N:P:K ratio (8:4:9) was used for the remaining fertigations.

Four monitoring wells were installed in each of the above two blocks. The monitoring well was 50 mm diameter with a 3.0 m screen, set about 1.5 m into the surficial groundwater. Each well had a 0.6 m $\times$ 0.6 m concrete pad and metal cover with padlock, and 4 bumper posts placed diagonally at four corners 0.6 m from the well. Within each block, four wells were distributed two wells per tree row on two rows at 175 m apart. The well was installed along the tree row between two trees at approximately 2.5 m from the tree trunk. Groundwater sampling was done at 14 day interval from January 1995, using a peristaltic pump (Cole-Palmer Instrument Co., Vernon Hills, IL). Sampling was done after purging five well volume of water. The tubing used in the sampling was cleaned in 1.0 M HCl followed by several rinses in distilled water. The concentration of $NO_3$-N in the water samples was analyzed by using ion chromatograph.

During 1995-96, the mean $NO_3$-N concentrations in the monitoring wells in the blocks ranged from 6.5 to 16.5 $mg \cdot L^{-1}$ and from 1.4 to 14.6 $mg \cdot L^{-1}$ where N was applied broadcast using WSG/CRF blend (Block 1) and fertigation (FRT; Block 2), respectively (Figure 5). This difference in mean groundwater $NO_3$-N concentrations between the two blocks was particularly striking following September 1995. Further, improved N and irrigation management practices did not adversely affect fruit production, despite a reduction in N rate per unit area. The fruit yields were greater for fertigation (FRT) treatment with 180 kg N/ha per yr as compared to the same rate applied as water soluble granular (WSG) fertilizer (Alva et al., 1998). This trend followed during 1995-97, and trend was reversed in 1998 (Table 2). Reversal of effects of N sources on fruit yield in 1998 compared to previous years was due to combination of tree topping, more tree damage in block 2 compared to block 1 due to stagnant water and greater tree replacement in block 2 compared to block 1. Nutrient status of trees, using the spring flush leaf

FIGURE 5. Comparison of effects of N source, and time of application on mean concentrations of $NO_3$-N in surficial groundwater samples collected during 1995 through 1999 from monitoring wells in Block 1 and 2 of N BMP demonstration experiment using 30+ year old 'Valencia' orange trees on 'Rough lemon' rootstock (Lake Placid, FL). Data represent means of 4 wells per block. The N applied as either water soluble granular (WSG) or fertigation (FRT) at 180 kg N/ha per yr. Arrows at the bottom of the X-axis indicate the water soluble granular fertilizer application events and timing of fertigations is shown along the x-axis. The horizontal dotted lines indicates the 10 mg·L$^{-1}$ $NO_3$-N maximum contaminant level (MCL) (Modified from Alva et al., 1998 with data from A.K. Alva, unpublished).




analysis, did not show significant differences between fertigation (FRT) vs. WSG treatments, with the former treatment appearing to increase the efficiency of nutrient uptake and utilization as evident from greater fruit yields compared to the latter (Alva et al., 1998).

## *Field Crops: Potato*

Nitrogen management for potato requires careful attention aimed to ensure adequate amount of N was made available during various growth stages to satisfy the crop requirement to attain optimum production of

TABLE 2. Fruit yield in N BMP demonstration experiment with 36-yr-old 'Valencia' orange on 'Rough lemon' rootstock grown in an Astatula fine sand in Lake Placid, FL (modified from Alva et al., 2003).

| Year | Block 1 (WSG + CRF) | | Block 2 (FRT) | |
|---|---|---|---|---|
| | kg N/ha per yr | Yield (Mg $ha^{-1}$) | kg N/ha per yr | Yield (Mg $ha^{-1}$) |
| 1995 | 180 | 52.2 | 180 | 60.4 |
| 1996 | 180 | 45.5 | 180 | 48.2 |
| 1997 | 180 | 55.1 | 180 | 66.5 |
| 1998† | 200 | 37.3 | 180 | 36.1 |

† Yield reduction in 1998 as compared to that in previous years was due to combination various factors such as wet winter followed by a dry spring, tree topping for the first time in several years, and a high rate of tree mortality.

high quality tubers. Therefore, timing and frequency of N applications and irrigation management are important to optimize the N uptake efficiency and minimize N losses. This is further complicated in sandy soils due to the low retention capacity of these soils for nutrients and water. Utilization of soil N is also limited by the shallow root system of potatoes (DeRoo and Waggoner, 1961; Lesczynski and Tanner, 1976; Delgado, 2001b), therefore, soil N only from a shallow depth can contribute to tuber production.

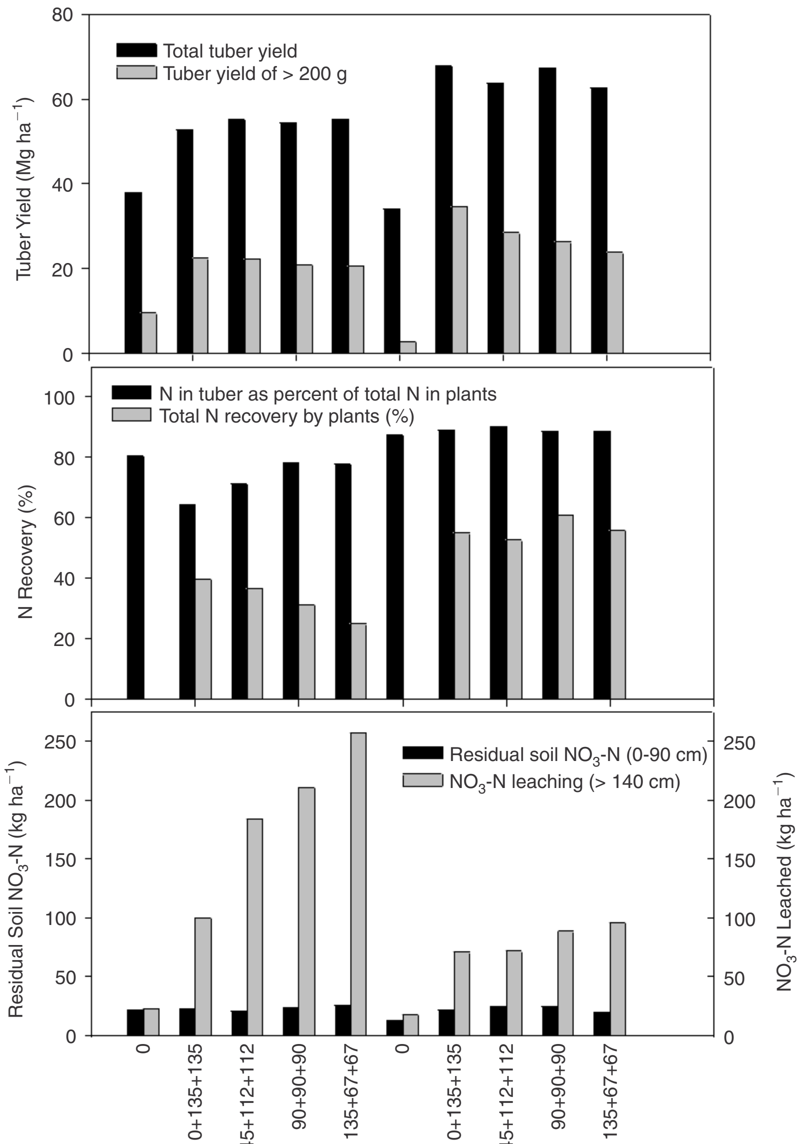
To overcome this problem, Iritani (1978) recommended application of one-third to one-half of the annual N rate at planting, and the remaining quantity applied during the growing season in several small doses. The seed piece supplies all the nutrients during planting through emergence. Even after emergence, early in the season, N requirement of the plant is rather low due to the small plant and limited root volume that occupies the soil. Therefore, the recommendation to apply one-third to one-half of annual N rate at planting may be questionable in relation to optimizing N uptake efficiency and minimizing the N leaching losses. Delgado et al. (1999) and Shoji et al. (2001) reported that under commercial potato operations of South Central Colorado 41.6% of the N was applied at planting, 33.4% at hill up and 24.9% with fertigation. The recommended rate for this region is about 50% at planting. The N use efficiency of the initial applied N was about 20% (Shoji et al., 2001). This is much lower than the 66% recovery for the N that was applied latter during the growing season at hill up and with fertigations (Shoji et al., 2001). Westermann et al. (1988) reported much higher N use efficiencies about 60 percent for preplant and 80 percent for in-season applications.

Vitosh and Jacobs (1990) suggested that N leaching potential is high when potato crop is supplied with excess N early in the growing season. Therefore, Westermann et al. (1988) demonstrated an increased N uptake efficiency by potato crop with multiple applications of N to facilitate the adequate availability of N over different growth stages. This response was also observed by Delgado et al. (1998b) and Shoji et al. (2001) as evident from a greater N recovery for the N that was split and applied at hill up and with fertigations. Additionally Delgado et al. (1999) and Shoji et al. (2001) reported that controlled release fertilizer applications at 139 kg N·ha$^{-1}$ had the same yields of the traditional commercial potato operations of 269 kg N·ha$^{-1}$. The N use efficiency of the controlled release fertilizer was 60.2% higher than the average 46.3% for the farmer traditional practices.

Errebhi et al. (1998a; 1998b) conducted a study to evaluate different N management practices on potato yield and $NO_3^-$ leaching below the rootzone. This study was conducted in Minnesota on a Hubbard loamy sand (sandy, mixed Udorthentic Haploboroll) using 'Russet Burbank' potato cultivar. Total N applied was 270 kg·ha$^{-1}$ as ammonium nitrate. The authors refer to this rate as the recommended N rate for irrigated potato production in North Dakota and Minnesota with a production target of 50 to 55 Mg·ha$^{-1}$. The irrigation water applied during the two years totaled 256 and 218 mm, respectively, which supplied 26 and 22 kg N·ha$^{-1}$ during the two years (Rosen 1991; 1993). Evaluation of $NO_3^-$ leaching was conducted by sampling soil solution for $NO_3$-N analysis at 140 cm depth using suction lysimeters. The water percolation was determined by water mass balance approach considering the precipitation, irrigation, change in water storage in the soil and evapotranspiration (Wright and Bergsrud, 1991). The N treatments evaluated included various combinations of N rates in kg·ha$^{-1}$ N at planting, emergence and hilling: (i) 0 + 135 + 135; (ii) 45 + 112 + 112; (iii) 90 + 90 + 90; (iv) 135 + 67 + 67; and, (v) a control treatment of no supplemental N during the entire growing period.

Results of the above study showed that the control treatment produced a total tuber yield of 38 and 34 Mg·ha$^{-1}$ during 1991 and 1992, respectively (Figure 6). Increasing the N application at planting from 0 to 135 kg·ha$^{-1}$ slightly increased the total tuber yield in 1991 (53 to 55 Mg·ha$^{-1}$), while decreased the tuber yield in 1992 (68 to 63 Mg·ha$^{-1}$). Increasing the proportion of N applied at planting decreased the yield of large size tubers, (i.e., > 200 g). Application of high N at planting de-

FIGURE 6. Effects of different N management practices on total tuber yield, yield of tubers >200 g size, total N recovery by the plants (%), N recovery in tubers as percent of total plant N, soil residual N, and $NO_3$-N leached below 140 cm depth. Nitrogen treatments are expressed as application in kg·ha$^{-1}$: at planting + emergence + hilling stages (Data from Errebhi et al., 1998).



layed the tuber bulking, therefore, decreased the production of large tubers while increased the production of small tubers. These results agreed with the conclusions of Westermann and Kleinkopf (1985). For maximizing potato yields and quality it is very important to applied N to best match the soil availability of N with the N best uptake needs that maximize yield and quality (Errebhi et al., 1998a; 1998b; Delgado et al.1998c; Shoji et al., 2001).

Errebhi et al. (1998a) also reported a rather low N recovery of 33 percent in 1991, which was a high rainfall year. The N recovery was 56 percent in 1992 (Figure 6). Total N content in the tuber was 63 and 73 $kg \cdot ha^{-1}$ during 1991 and 1992, respectively, for the 0 N treatment. In the N applied treatments, N content in the tuber varied from 119 to 127 $kg \cdot ha^{-1}$ in 1991, and 203 to 219 $kg \cdot ha^{-1}$ in 1992. Residual soil N in the top 90 cm depth soil after the potato harvest was about 20 to 25 $kg \cdot ha^{-1}$ both years regardless of N management treatments (Figure 6). This suggests that the N applied in various N management treatments was either taken up by the crop and/or leached below the depth of soil sampling. The authors also calculated the amount of N leached during the growing season using the $NO_3$-N concentration measured in suction lysimeter samples. The amount of N leached varied from 100 to 257 $kg \cdot ha^{-1}$ in 1991, and 71 to 96 $kg \cdot ha^{-1}$ in 1992. The results showed an increased $NO_3$-N leaching in high rainfall season and a clear increase in the amount of $NO_3$-N leached with an increase in N rate applied at planting. Much of the $NO_3$-N leaching occurred during the period between planting and emergence. Errebhi et al. (1998a) demonstrated that application of high rate of N at planting for irrigated potato in sandy soils was not beneficial in terms of tuber yield. Furthermore, this practice resulted in increased leaching of $NO_3$-N below the rootzone. Accordingly, the authors recommended to decrease the amount of N applied at planting for 'Russet Burbank' potato under irrigated conditions in sandy soils.

Prins et al. (1988) reported N recovery in potato tubers in the range of 90 to 150 $kg\ N \cdot ha^{-1}$ for growing conditions in the Netherlands. Under the production conditions in south Ontario, Canada, Hill (1986) reported N recovery in tubers in the range of 75 to 127 $kg \cdot ha^{-1}$. For 'Russet Burbank' potato grown in sandy soils in Wisconsin, total N recovery in tubers varied from 135 to 180 $kg \cdot ha^{-1}$ (Saffigna et al., 1977). Alva et al. (2002) reported N recovery in tubers of about 212 $kg\ N \cdot ha^{-1}$ for 'Russet Burbank' in sandy soil in the Pacific Northwest, with tuber production up to 70 $Mg \cdot ha^{-1}$.

*Nitrogen Requirement for Tuber Growth*

Fertigation is an important method of delivery of nutrients for potato production. This practice allows greater flexibility of timing of fertilizer application. Nitrogen fertilizer uptake efficiency is generally 60 percent for preplant and 80 percent for in-season applications (Westermann et al., 1988). Daily nutrient uptake rates vary considerably between different varieties which is indicative of the varietal differences in tuber growth rates, thus, differences in N uptake rates. Westermann and Davis (1992) reported a wide range of tuber growth rates, i.e., 850 to 1460 kg/ha per day, across 10 varieties. Nitrogen utilization rates varied from 2.0 to 5.8 kg/ha per day during tuber growth period. The tuber growth rate was the highest for Kennebec cultivar (1460 kg/ha per day) while it was the lowest for Norchip cultivar (780 kg/ha per day). The N uptake rates for the above two cultivars were 3.7-5.8 and 2.0-3.1 kg/ha per day, respectively. The tuber growth rate of 'Russet Burbank' cultivar was 850 to 950 kg/ha per day with N uptake rates of 2.4 to 4.0 kg/ha per day.

The recommended optimal concentration of N and P in the tubers were 15.5 and 2.0 $g \cdot kg^{-1}$, respectively. Using the above optimal tuber N concentrations for 'Russet Burbank' and a daily growth rate of 950 $kg \cdot ha^{-1}$ (at 21 percent dry matter content in the tuber), 3.0 kg N/ha per day required to satisfy this growth. If we consider the tuber bulking period of about 60 days, the total N need during tuber bulking period for optimal tuber growth would account for about 180 $kg \cdot ha^{-1}$.

To promote early tuber development and to increase NUE, it is necessary to apply N fertilizers to potato before or at planting and small amounts applied in the irrigation water during the growing season. A clear understanding of seasonal N uptake pattern by potato is necessary to adequately schedule timing of N applications to optimize tuber yield, tuber grades and N fertilizer efficiency. Under high N rate applications (440 $kg\ N \cdot ha^{-1}$), vines are the dominant sink for N. A study in Wisconsin showed no significant difference in total N uptake by the tubers with 4 applications for a total of 260 $kg\ N \cdot ha^{-1}$ vs. 11 applications for a total of 170 $kg\ N \cdot ha^{-1}$, although the vine N uptake was greater in the former compared to the latter treatment (Saffigna and Keeney, 1977; Saffigna et al., 1977).

Lauer (1984) conducted a study using 'Russet Burbank' potato planted on a loamy Quincy fine sand (mixed, mesic, Xeric Torripsamments). Before planting, 100 $kg\ N \cdot ha^{-1}$ was broadcast and incorporated into the soil. In season N was applied using urea plus ammonium nitrate solution (UAN) through irrigation system to vary the N rate with total N in the range of 100 to 610 kg·ha$^{-1}$. The in season N application began 17 and 28 days after emergence, respectively, in 1980 and 1981 with 70 to 74 daily applications of N through sprinkler irrigation. Irrigation was scheduled based on pan evaporation. With 610 kg·ha$^{-1}$ N rate, the tuber yield was 60 Mg·ha$^{-1}$ and total maximum N uptake was 574 kg·ha$^{-1}$ at 94 days after emergence. At this time, the total N in vines and tubers was 344 (60 percent) and 230 (40 percent) kg·ha$^{-1}$, respectively. At 28 days after emergence, vines were the dominant N sink with N uptake rates varying from 4.0 to 7.0 kg N/ha per day. By 72 days after emergence, the tuber N uptake rate was of 3.8 kg N/ha per day which exceeded the vine N uptake rate. By this growth stage, the tuber became the dominant sink for N.

Despite the loss of N from vine due to leaf drop towards the end of the season, the vines contained greater amount of N than that in the tubers, thus, represented the dominant N sink through most of the growing season, under heavy N rate fertilization. However, in the 210 kg·ha$^{-1}$ N treatment, tubers became the dominant N sink at or near the onset of tuber formation, with only 1.8 kg N/ha per day uptake rate. Tuber yield was 63 Mg·ha$^{-1}$ with 210 kg·ha$^{-1}$ N rate, which was quite similar to that in the 610 kg·ha$^{-1}$ N rate. In the 210 kg N·ha$^{-1}$ treatment, total N uptake was 230 kg·ha$^{-1}$, which was distributed between tuber and vine at 63 and 37 percent, respectively. Total N uptake was 2.5-fold greater with 610 compared to that with 210 kg·ha$^{-1}$ N rate treatment. However, the tuber yield was slightly greater (by 3 Mg·ha$^{-1}$) with the latter as compared to that with the former N rate. The N removals by the tuber at the end of the season were 250 and 180 kg N·ha$^{-1}$, respectively, for the 610 and 210 kg·ha$^{-1}$ N rates. Application of N at rates above the optimal amount results in excessive N uptake by vines as well as tubers with no increase in tuber yields. Excessive N applications increased the vine dry matter as well as N concentrations. Increased vine growth at maturity results in increased amount of N being returned to the soil as leaf drop at the end of the growing season. The breakdown of the N from vegetative debris upon mineralization results in an increase in available forms of N after the crop is harvested and can contribute to $NO_3^-$ leaching. On the basis of this study and other unpublished data, Lauer (1984) recommended 340 kg N·ha$^{-1}$ as the optimal N rate for sandy soils in the Columbia Basin. Good N management for potato consists of conditions favorable for translocation of N from vines to the tubers. Multiple applications of N in small quantities through irrigation water during tuber development stage promotes increased N availability to the tubers, thus, enhances the N uptake efficiency.

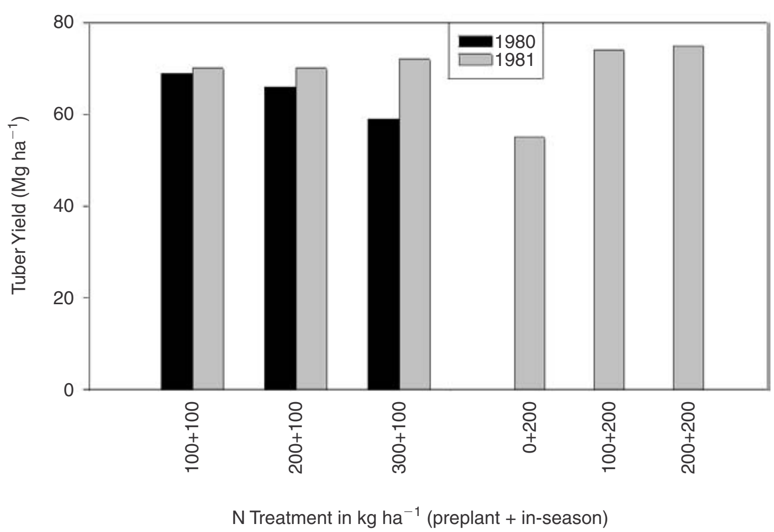
Potato is particularly sensitive to soil compaction. Plow pan restricted potato root growth to the plow layer in silt loam and coarse textured soils. External tuber quality can be affected by compaction. The effect of soil compaction on production and quality of potato is due to multitude of effects on root growth, nutrient movement and uptake. Restricted root growth due to soil compaction can result in negative impact on the nutrient and water uptake due to a limited zone of soil being tapped and/or the root's limited capacity to extract soil zone with limited nutrient and water availability.

Westermann and Sojka (1996) studied the effects of fall tillage (disking, chiseling, and moldboard plowing), and N placement (220 kg $N \cdot ha^{-1}$ as urea ammonium nitrate; either broadcast and immediately tilled in, or banded 0.12 m to the side of the seed piece) on tuber yield and quality of potato (cv. 'Russet Burbank') planted after winter wheat (1989) or dry bean (1990) on a Portneuf silt loam soil. They also evaluated the effects of zone subsoiling after spring planting. This was done with paratill shanks after hilling. Fall tillage did not influence nutrient concentrations or uptake, tuber yield or quality. Deep tillage increased plant dry weights by 9 percent, tuber yields by 10 percent and increased P uptake by 12 percent. Banding N increased average plant dry weight by 64 percent, total tuber yield by 9 percent and N uptake by 28 percent compared to those with broadcast treatment. Zone subsoiling treatment increased the U.S. No. 1 tuber yield from 24.8 to 28.3 $Mg \cdot ha^{-1}$ and from 24.3 to 34.0 $Mg \cdot ha^{-1}$ and total tuber yield from 39.5 to 41.2 $Mg \cdot ha^{-1}$ and from 44.8 to 52.5 $Mg \cdot ha^{-1}$ in 1989 and 1990, respectively, in N banded treatment. Similar magnitude of yield increase was also evident in N broadcast treatment. In 1989, banding N consistently increased the whole plant N uptake in both sampling dates regardless of zone subsoiling treatment. In 1990, however, the N placement method had marginal effects on whole plant N uptake in the second sampling date only. Petiole $NO_3$-N was also much greater in the plants which received N banded as compared N broadcast treatment at the same N rate in 1989 only. The above differences in N uptake appears to be related to the difference in preceding crop to potato, which was wheat in 1989 compared to bean in 1990.

Lauer (1984; 1986) conducted a study using 'Russet Burbank' grown on a Quincy fine sandy soil (mixed, mesic Xeric Torripsamments) in Washington. The paper reported no data on the residual soil N at the time of planting. The treatments included preplant broadcast application of either 100, 200, or 300 kg $N \cdot ha^{-1}$ as urea and ammonium nitrate and in season application of 100 kg $N \cdot ha^{-1}$. No information was provided on the frequency of in season N application. In year two of the study, there were three additional preplant N rates treatments at either 0, 100, or 200 kg N·ha$^{-1}$ with 200 kg N·ha$^{-1}$ in season rate. During the first year of the study, the total tuber and U.S. No. 1 tuber yield significantly decreased at the 300 kg N·ha$^{-1}$ preplant N treatment. During the second year of the study, the tuber yield was the lowest with no preplant N application despite 200 kg N·ha$^{-1}$ was applied in season (Figure 7). The yield significantly increased with 100 kg N·ha$^{-1}$ each of preplant and in season applications. Increasing the preplant N rate to 200 or 300 kg N·ha$^{-1}$ had no significant effects on the tuber yield. A further significant yield increase was obtained with application of 200 kg N·ha$^{-1}$ in season with either 100 or 200 kg N·ha$^{-1}$ of preplant N. These latter treatments were used only in the second year. Thus, one year response data are inadequate to make reliable conclusions on N management. The mean U.S. number one tubers as compared to the total tuber yield accounted for 79 and 71 percent, respectively, in 1980 and 1983.

Roberts et al. (1991) conducted a study using 'Russet Burbank' on a Quincy loamy sand (soil pH of 5.7; 0.45 percent organic carbon and 0.04 percent organic N), with application of 336 kg N·ha$^{-1}$ total N. Of

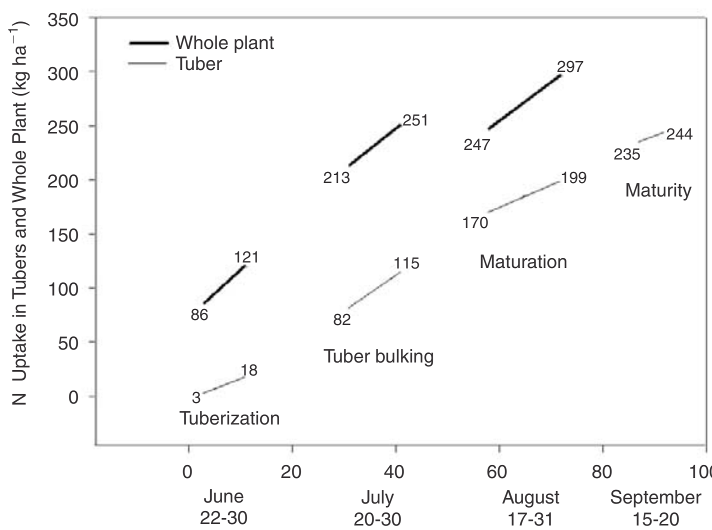
FIGURE 7. Total tuber yield of 'Russet Burbank' variety grown in a Quincy fine sand which received different rates of pre-plant and in-season N application in two year study (Data from Lauer, 1986).



this amount, 112 kg N·ha$^{-1}$ was applied at planting using 3 percent $^{15}N$ enrichment with either $^{15}NH_4^+$ or $^{15}NO_3^-$. The remaining quantity of N was applied as either 8 (in 1981; applied at 10 d interval with 28 kg/ha per application) or 10 (in 1982 and 1983; applied at 7d interval with 22.4 kg/ha per application) applications in season using $^{15}NH_4$ or $^{15}NO_3^-$. The N uptake in the whole plant during early maturation (in August) was up to 297 kg N·ha$^{-1}$ (Figure 8). Of this total amount, about 244 kg N·ha$^{-1}$ was present in tubers, which represented 80 percent of the whole plant N. Potato yield in this study was up to 74 Mg·ha$^{-1}$ which is representative for this production region. The highest recoveries of $^{15}N$ in whole plants were 61, 67, and 65 percent in 1981, 1982, and 1983, respectively. These recoveries were obtained when labeled N source was applied during tuberization to tuber bulking growth stages. The study also demonstrated the importance of maintaining adequate N availability in the soil during tuber bulking stage as evident from high recoveries of labeled N applied during this stage.

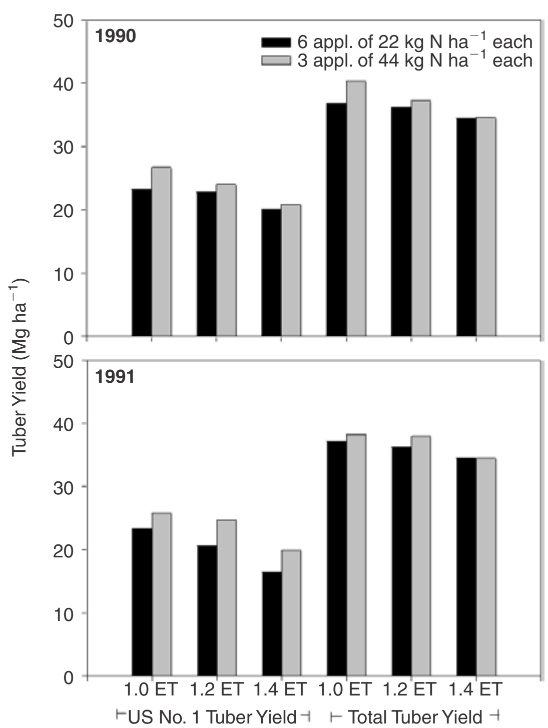
Stark et al. (1993) evaluated the effects of three irrigation regimes (1.0, 1.2, and 1.4 fold of crop evapotranspiration-ET) and two N frequencies (either 22 kg N·ha$^{-1}$ weekly applications for 6 weeks or 3 ap-

FIGURE 8. Nitrogen uptake by tubers and whole plant of 'Russet Burbank' variety, at various growth stages, grown on a Quincy fine sand (Data from Roberts et al., 1991).



plications of 44 kg N·ha$^{-1}$ every two weeks; starting at tuber initiation, i.e., July 5) on 'Russet Burbank' potato cultivar grown on a Declo silt loam soil (coarse, loamy, mixed mesic, Xerollic Calciorthid) in Idaho. In-season N was applied as urea-ammonium nitrate (UAN) through the sprinkler system, with a total of 132 kg N·ha$^{-1}$. The residual soil N in the top 30 cm depth soil was 72 and 52 kg N·ha$^{-1}$ during two years of the study. No N was applied during preplanting. The total tuber yields varied from 34 to 40 Mg·ha$^{-1}$, and 34 to 38 Mg·ha$^{-1}$ during the two years (Figure 9). During the first year of the study, the tuber yields significantly decreased from 39 to 34 Mg·ha$^{-1}$ with an increase in irrigation regime from 1.0 to 1.4-fold ET. The irrigation effect was non-significant during the second year. Nitrogen frequency effect was non-significant during both years. However, in both years, the U.S. No. 1 tuber

FIGURE 9. Effects of different irrigation regimes and in-season N application frequencies on total and U.S. No. 1 tuber yields of 'Russet Burbank' variety grown on a Declo silt loam soil in Idaho (Data from Stark et al., 1993).



yield decreased significantly with increased irrigation, as well as with increased frequency of N application (6 applications of 22 kg $N \cdot ha^{-1}$ each vs. 3 applications of 44 kg $N \cdot ha^{-1}$ each). Increased irrigation decreased the tuber specific gravity both years. A significant decrease in tuber specific gravity was also evident with increased frequency of N application in one year only. This study revealed the negative effects of excess irrigation which could be attributed to the secondary effects of poor aeration. The plants grown in high water regime treatment exhibited chlorotic vines and leaves, and tubers with enlarged lenticels. This is in agreement with results of Holder and Cary (1984). The excess irrigation increased the $NO_3$-N leaching from the soil and decreased the N availability to the plants as was evident from lower petiole $NO_3$-N concentration during substantial portion of tuber bulking period as compared to those of the plants grown in optimum irrigation treatment.

Joern and Vitosh (1995) conducted three trials in Michigan on 'Russet Burbank' to evaluate the effects of the following N treatments: (i) at planting N application of either 0, 56, or 112 kg $N \cdot ha^{-1}$; (ii) two applications of 56 kg $N \cdot ha^{-1}$ each at planting and at tuber initiation; (iii) three applications of 56 kg $N \cdot ha^{-1}$ each at planting, tuber initiation, and 14 days after tuber initiation; (iv) four applications of 28 kg $N \cdot ha^{-1}$ each with one at planting and the 3 applications at 14 days interval after tuber initiation. In two out of three trials, total and U.S. No. 1 tuber yields increased with an increase in applied N rates at planting. Overall, at a given total N rate treatment, the split application of N failed to show any benefits as compared to single application of the full N rate. Prolonging the timing of N application during the in-season at the expense of reduced N rate at planting appeared to decrease the tuber yield. It is important to recognize that these studies were done in somewhat heavy textured soils with organic matter contents in the range of 16 to 19 $g \cdot kg^{-1}$. These soils are less vulnerable to rapid leaching of water and soluble nutrients below the rootzone, therefore, are able to store the nutrients in the rootzone much longer as compared to the sandy Entisols used in much of the potato industry in the Pacific Northwest. In the latter soils, excess leaching of soluble nutrients could occur particularly under heavy irrigation. Therefore, in light textured soils with lower organic matter content, multiple applications of N in small doses is preferred compared to single application at planting of the total N required for the entire growing period. The tuber yield across all treatments varied from 30 to 35 $Mg \cdot ha^{-1}$ and were unaffected by the various treatments. The N concentrations in the tuber varied from 9.5 to 17.6 $g \cdot kg^{-1}$. Since optimal tuber N concentration is 15.5 $g \cdot kg^{-1}$ (Westermann and

Davis, 1992), the tuber N concentrations in this study were below the optimal in one trial across all treatments despite tuber yields varied from 25 to 50 Mg·ha $^{-1}$. In another trial, tuber N concentrations were in the range of 15.3 to 17.6 g·kg$^{-1}$, thus greater than the optimal recommended concentration in all treatments. This study showed that tuber yield was not related to tuber N content. Tuber N content at harvest varied from 95 to 120, 50 to 120, and 50 to 100 kg·ha$^{-1}$, respectively, in the three trials.

Nitrogen and irrigation managements are critical for potato production to attain optimal yield of marketable quality tubers while minimizing the negative impacts on the environment that can arise due to $NO_3^-$ leaching below the rootzone. Nitrogen use efficiency can be increased by low preplant N application, but maintaining adequate N during tuber development by multiple in-season applications (Westermann and Kleinkopf, 1985). The sandy soils have low N retention capacity, therefore, multiple applications at low quantities is preferred as compared to less frequent applications of larger rates. This is particularly important for potatoes because of shallow root systems (DeRoo and Waggoner, 1961; Lesczynski and Tanner, 1976).

### *Field Cropping Systems: Rotation of Shallow- and Deep-Rooted Crops*

It is important to use a sequential cropping system approach to evaluate the N use efficiency of a system (Delgado, 1998). The $NO_3^-$ leaching losses must be evaluated considering the rooting depth of the deeper rooted crop of the system (Delgado, 1998). Scavenger deep rooted crops can recover $NO_3^-$ deep in the profile that was leached out of the shallower rooted crops (Delgado, 1998). We must also consider management zones (soil types), yields (sink of N), cycling from crop residue, site specific hydrologic and site specific N cycling properties when evaluating NUE and $NO_3^-$ leaching of cropping systems (Delgado, 1999; Delgado, 2001a).

#### *Rationale and Description of the Study*

The San Luis Valley (SLV) of south central Colorado is a high altitude intermountain dessert valley located in south central Colorado with the Sangre de Cristo Mountains to the east and the San Juan Mountains to the west. The area cover by the valley is about 8288 km$^2$ at an average elevation of 2348 m (Edelmann and Buckles, 1984; Hearne and Dewey, 1988). Since the average precipitation in this area is 168 mm, intensive agriculture requires irrigation. The Spanish-American settlers were the first to practice irrigation in this area by diverting water from the Rio Grande. Later at the end of the nineteenth century the use of surface irrigation was greatly expanded with the development of an intensive network of channels. Intensive use of groundwater began during the middle of the twentieth century with the development of high capacity pumps (Hearne and Dewey, 1988). Water use efficiency was improved for the region with the use of sprinkler irrigation that started in the 1970s and expanded rapidly from 262 wells in 1973 to over 2000 by 1996.

Austin (1993) conducted an inventory of domestic well water $NO_3^-$ status concentrations and reported concentrations as high as 37 $mg \cdot L^{-1}$ $NO_3$-N. Other surveys of irrigated wells found concentrations as high as 70 $mg \cdot L^{-1}$ (Eddy-Miller, 1993). It has been reported that the combination of N fertilizer use, shallow ground-water supplies, sandy soils that cover most of the area, and irrigated agricultural systems contribute to elevated $NO_3$-N concentrations (Eddy-Miller, 1993). There is the need to evaluate the use of BMPs and the potential to use new tools to evaluate N and water management for conservation of water quality.

### *Multidisciplinary Committee Approach for Development of Best Nutrient Management Practices*

In 1991 the USDA authorized the San Luis Water Quality Demonstration Project to promote the development and use of Best Management Practices for this region of south Central Colorado. Cooperation was established among farmers, Colorado State University, advisors, state government, USDA-NRCS and USDA-ARS scientist to conduct studies across the region to evaluate current and new BMPs (Delgado et al., 1998a; 1998c; Delgado 2001b; Ristau, 1999). From 1992 to 1997, the USDA-ARS-Soil Plant Nutrient Research Unit in cooperation with Colorado State University, farmers, NRCS and other cooperators conducted to facilitate technology transfer efforts to evaluate BMPs (Delgado et al., 1998b). The results of these studies were published by the Colorado State University Extension Bulletin *Best Management Practices for Nutrient and Irrigation Management Practices in the San Luis Valley* (Ristau, 1999).

One key component of this project was the development of a BMP advisory committee (Ristau, 1999). This committee was composed of 21 members, including ten producers. The final BMPs publication covered integrated cropland cultural practices, N and P management, irrigation management, manure and organic waste utilization and other BMP to improve nutrient and irrigation management practices (e.g., models for nutrient and irrigation management). This BMP publication was supported and endorsed by the local producers of the region (Ristau, 1999). It is important to incorporate the final users, the landowners in the development of BMP. A new version of the NLEAP model was developed (Delgado et al., 1998c). The needed parameters were collected to run the model and assessment of the effects of BMP on N and water budget was conducted (Delgado, 2001b).

*Use of Winter Cover Crops:*
*Lettuce-Winter Cover Crop-Potato Rotation*

Potential wind erosion in south central Colorado is greater in the spring, especially after potato and lettuce fields that leave little crop residue after harvesting. Winter cover grains (WCG) such as wheat (*Triticum aestivum* L.) and rye (*Secale cereale* L.) provide maximum soil and water conservation when they are planted early in the fall and have more degree days for vegetative growth before growing is reduced during winter (Delgado et al., 1999). At a commercial lettuce-winter cover crop-potato rotation, the winter cover crop rye responded spatially to levels of residual soil $NO_3$-N scavenging higher $NO_3$-N at the areas with higher residual soil $NO_3$-N. The scavenger crop planted after lettuce reduced the residual soil $NO_3$-N left from 206 to 30 kg $NO_3\text{-N}\cdot ha^{-1}$ in the high areas and from 123 to 30 kg $NO_3\text{-N}\cdot ha^{-1}$ in the areas with lower residual soil $NO_3$-N. Total N uptake for the winter cover rye in the high residual soil $NO_3$-N areas was 179 kg $N\cdot ha^{-1}$, similar to the 176 kg $N\cdot ha^{-1}$ reduction in residual soil $NO_3$-N. For the low residual soil $NO_3$-N areas the total uptake of 91 kg $N\cdot ha^{-1}$, also in close agreement with the 93 kg $N\cdot ha^{-1}$ observed reduction in residual soil $NO_3$-N. Dry matter production that served as a source of protection against wind erosion, returned an average of 7.4 Mg dry biomass$\cdot ha^{-1}$ for the highest residual soil $NO_3$-N areas with a C/N ratio of 17.7, greater than the 4.6 Mg dry matter$\cdot ha^{-1}$ with a C/N ratio of 14.7 at the lower residual soil $NO_3$-N areas. The winter cover crop was killed early in the spring when the C/N ratios were lower than 20, so the incorporated biomass served as a green manure with a greater N fertilizer equivalency (Doran and Smith, 1991).

Another benefit of the winter cover rye after lettuce is that it reduces the potential for $NO_3^-$ leaching by the following potato crop (Delgado, 1998). If we plant shallower high N input crops year after year, we will expect to have greater quantities of $NO_3$-N at planting. For example, a field that was continuously planted with spinach for over 20 years had a residual soil N of 829 kg $NO_3$-N in the top 90 cm soil layer (Delgado et al., 1999; Dabney et al., 2001). It is clear from Delgado (1998), Delgado et al. (1999) and Dabney et al. (2001) that rotating high N input crops such as potato, lettuce and spinach with scavenger crops such as small grains or winter cover crops reduces the potential $NO_3$-N available to leach during the growing season of the shallower rooted crops. The initial residual soil $NO_3$-N concentrations at planting will be lower.

Crop rotations are universal tools that can be used to increase the NUE of irrigated systems (Delgado et al., 1998a; 1999; 2001a; 2001b; Meisinger and Delgado, 2002). The rotation of winter cover crops can potentially increase NUE, protect soil quality, recover $NO_3$-N from irrigation water (increase $NO_3$-N mining), and reduce $NO_3$-N leaching for the following crop (Meisinger et al., 1991; Dabney et al., 2001; Delgado et al., 1999; Delgado 1998). Winter cover crops can recover up to 300 kg $N \cdot ha^{-1}$ from the soil profile that can be returned to the surface soil (Delgado et al., 1999). Several researchers have reported use of WCC to scavenge $NO_3$-N (Jones et al., 1977; Groffman et al., 1987; Shipley et al., 1992; Holderbaum et al., 1990; Meisinger et al., 1991; Brinsfield and Staver, 1991; Decker et al., 1994; McCracken et al., 1995). Dabney et al. (2001) discussed the potential benefits of WCC use.

### *Use of Winter Cover Crops: Grazing*

Beside the benefits or scavenging $NO_3$-N and reducing wind erosion, farmers can use winter cover crops for grazing and have another source of income (Redmon et al., 1995; Delgado et al., 1999; Delgado and Follett, 1998). It has been reported that cattle could get weight gain by grazing winter cover crops, but there is a risk of death due to bloating or other physiological problems (Clay 1973a; 1973b; Johnson 1973; Bartley et al.,1975; Horn et al., 1977; Mader et al.,1983). Winter cover crops such as wheat and winter rye can accumulate forage $NO_3$-N at levels that can be potentially toxic to animals (Tucker et al., 1961). Grazing of winter cover crops on a farm in the San Luis Valley that had 3500 mg $NO_3\text{-}N \cdot kg^{-1}$ caused bloating in steers. The livestock had to be removed or grazed using the rye with supplemental hay that was brought into the field (Delgado et al., 1999).

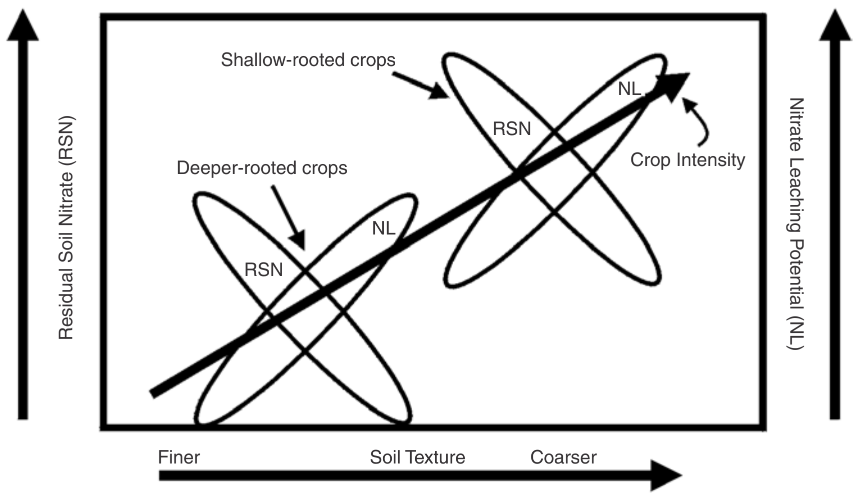
We could expect significant amounts of N cycling back to the system (Delgado and Follett, 2002). Follett and Wilkinson (1995) reported that for a 250 kg steer, that ingest 6 kg of forage day$^{-1}$, will recycle about 88.9 percent of the 0.18 kg N·d$^{-1}$ ingested. About 74 percent of the N recycled by grazing animal was in the urea form (Follett and Wilkinson, 1995). Grazing of winter cover crops will be another source of income to the farmers and will contribute to recycle significant quantities of N back into the soil. The distribution of recycled N by the grazing animal is not uniform over the entire field. A significant portion of this recycled N is subject to loss by $NH_3$ volatilization (Schimel et al., 1986). In the spring, the farmer has the option of incorporating the winter cover crop as a green manure (Delgado et al., 1999).

*Shallow-Rooted Vegetable Crops and Deep-Rooted Grain Crops*

For south central Colorado the commercial fertilizer application rate to lettuce (297 kg N·ha$^{-1}$) and potato (210 kg N·ha$^{-1}$) are greater than those applied to malting barley (42 kg N·ha$^{-1}$). The recommended initial soil $NO_3$-N at planting of shallow rooted crops for this region is on average about 30 kg N·ha$^{-1}$ (e.g., lettuce-barley), while it is 100 kg N·ha$^{-1}$ for small grains (Delgado, 2001a). The variability of this residual soil $NO_3$-N is also field specific and management zone specific within a field (Delgado, 1999; Delgado, 2001b). Variability in N status in a field can be quite significant, for example, 100 to 225 kg N·ha$^{-1}$ within a field with the same management practices. The spatial variability of these zones was observed by Delgado (1998; 1999; 2001b). On an average the residual soil $NO_3$-N for center pivot irrigated barley, canola and potato grown on a loamy sand zone was 20, 44 and 109 kg N·ha$^{-1}$, respectively. The sandy loam zone had a greater residual soil N of 42, 51, and 136 kg N·ha$^{-1}$, respectively. The amount of residual soil N was negatively correlated with the amount of N leached out of the site specific zone (Delgado, 2001a). On an average the $NO_3$-N leached from a soil irrigated by a center pivot system with barley, canola and potato on a loamy sand zone were 32, 39 and 91 kg N·ha$^{-1}$, respectively. The sandy loam zone had a significantly lower leaching of 29, 13, and 72 kg N·ha$^{-1}$, respectively.

Based on Delgado (2001b), we could develop an assessment of the effect of crop intensity and soil texture on residual soil $NO_3$-N (RSN) and $NO_3$-N leaching (NL). Figure 10 shows that with best management practices, as we increase the cropping intensity (higher N inputs), the RSN and NL from the root zone increased for irrigated systems. How-

FIGURE 10. Effects of crop species, intensity of crop management, and soil texture on residual soil nitrogen and nitrogen leaching (Data from Delgado, 2001b).




ever, within the same management and cropping system, the RSN was lower while NL was greater in a coarser textured soil as compared to those in a finer textured soil. These concepts are important and must be considered when developing a national $NO_3$-N leaching index as described by Shaffer and Delgado (2002). Delgado (2001a) studies were conducted in coarse, well-drained, sandy soils, thus, under negligible denitrification losses. Where denitrification is a factor, this process must be considered in the developing of an index since $NO_3$-N could be lost to the atmosphere (Shaffer and Delgado, 2002). We also need to keep in mind that we could use other practices such as crop rotations and winter cover crops to recover some of this leached $NO_3$-N leached out of the root zone. Additionally, that with best management practices that better match the delivery of N to the crop N uptake, the potential of $NO_3$-N leaching and residual soil $NO_3$-N will be reduced.

## *CONCLUSIONS*

With so many cropping systems and variabilities, modeling becomes a significant tool to evaluate the potential to use BMPs to reduce $NO_3$-N leaching losses and increase water N uptake efficiencies. Numerical modeling can simulate water and N budgets to evaluate irrigation systems and the transport of $NO_3$-N in the soil profile and $NO_3$-N leaching losses. Models have been used to evaluate the effect of BMPs on N uptake efficiency and $NO_3$-N leaching losses (Delgado, 2001a). Users have the flexibility to choose the detail of information needed to evaluate a specific practice and the time or frequency interval that is desired. Nutrient managers can choose from general basic index model to a very detail research numerical model.

The internet and recent advances on modeling have made models available to all types of users. Non-modelers now can use models to conduct site specific analyses at a local level. Scientists, agronomists, extension personnel, consultants, and farmers can use these models to improve N management. Model has been proposed to be used to develop a National Nitrate Leaching Index (NLI) assessment tool to help identify potential 'hot spots' and susceptible areas. Shaffer and Delgado (2002) recommended that the development of a National Nitrate Leaching Index should be internet based to have quick assess to the latest version of the model and databases. Numerical modeling tools are here to stay and will become more widely used to contribute to the development and implementation of more efficient N and irrigation management practices.

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