Nitrogen and Irrigation Management Practices to Improve Nitrogen Uptake Efficiency and Minimize Leaching Losses

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SUMMARY. Nitrogen (N) is the most important nutrient for plant growth and production. Nitrogen uptake efficiency is dependent on a number of factors. Water management influences the transformation of

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N sources applied to the soil and transport of the nitrate form of N in the soil. Nitrate-N is the final product of N transformations and is quite mobile in soils with the water front. Leaching of nitrate below the rootzone is an economic loss and contributes to non-point source pollution of groundwater. In this chapter we summarize the factors influencing the N uptake efficiencies for various crops and production systems, and chemical and biological processes that influence the N transformation or losses. Recent advances leading to development of N and irrigation best management practices that support sustainable crop production and net returns while minimizing the non-point source nitrate pollution of groundwater are also discussed.

KEYWORDS. Best management practices, cover crops, drinking water quality, fertigation, groundwater nitrate pollution, irrigation management, monitoring crop N status, nitrification, non-point source pollution, precision farming, volatilization

INTRODUCTION

Importance of Nitrogen as a Plant Nutrient

Accommodating the needs of expanding world population requires a highly productive agriculture that conserves resources while preserving the quality of the environment. Various nutrient elements are essential for plant growth and needed for maintaining sustainable and productive agricultural systems. Among all these essential elements, nitrogen (N) is ranked in the top in terms of total quantity and is required in large quantities for agricultural production. Although N can be present in the soil in many different forms, the most common forms absorbed by non leguminous crops are nitrate-N (NO_3-N) and ammonium-N (NH_4-N). Plant absorbed NO_3-N is readily mobile and can be rapidly transported, reduced and used for the synthesis of proteins.

Nitrogen is an essential element and key component of the deoxyribonucleic acid (DNA), ribonucleic acid (RNA), essential amino acids and proteins. Nitrogen is also an important structural component of the chlorophyll molecule which is necessary for the photosynthetic process. Nitrogen deficiencies lead to chlorotic symptoms, and reduced photosynthates which ultimately results in lower yields. Optimal N availability results in green foliage color and increased crop yields, however, excess N can lead to decreased yields due to luxury consumption.

The productivity of many current cropping systems depends heavily upon the use of industrially produced N fertilizers. Among the industrially produced N fertilizers, NH_4-N fertilizers are being used extensively in western agriculture, while urea is the major source in the eastern part of the world. All sources or forms of N fertilizers applied to soil go through various transformations to produce different intermediate forms and finally convert to NO_3^- form. Information on reactions such as adsorption, fixation and immobilization of NH_4^+ applied to the soil directly or transformed due to hydrolysis and mineralization, is of great importance. These processes facilitate minimizing N losses through volatilization, denitrification and leaching, thereby helping to retain N in the soil for a longer period of time. Management techniques to increase the N retention in soils and minimize various losses are the basis to develop management alternatives to improve N fertilizer uptake efficiency.

USDA-NRCS (2000) reported that about 17 percent of the U.S. cropland is under irrigation. Approximately 75 percent of all irrigated croplands in the U.S. are located west of the Mississippi river. Several researchers have reported two-fold greater yields of most crops in irrigated farming as compared to that in rain-fed production conditions (Rangely, 1987; Bucks et al., 1990; Tribe, 1994). Water and fertilizer management are linked in such a way that changes in one program will affect the efficiency of the other program. Plants take up inorganic N contained in the water absorbed from soil solution through their root systems. Thus, the fate of N is certainly coupled to that of water reaching the soil in the root zone. Leaching potential is high for the mobile nutrients such as nitrate (NO_3-N), and potassium (K^+); therefore, excessive irrigation and rainfall, or either, can result in movement of these nutrients out of the root zone. If we are going to improve N uptake efficiencies for irrigated systems we need to do it within the context of the N and hydrologic cycles considering site specific factors and crop growth status.

Nitrogen Use and Water Quality Impacts

The drinking water standard for NO_3-N is 10 mg per liter, which was recommended in 1962 by the World Health Organization and U.S. Public Health Service (U.S. Department of Health, Education & Welfare, 1962). This concentration limit has been adapted by the U.S. Environmental Protection Agency (USEPA, 1989) as the Maximum Contaminant Limit (MCL) of NO_3-N in drinking water, which has been used as the health advisory standard for drinking water. Although there is some controversy with respect to the validity of this NO_3-N concentration as the maximum contaminant level (MCL), in the U.S. all states are required to follow this standard. Accordingly, the same standard also applies to the aquifer as well as the soil water that contributes to recharging the aquifer. In agricultural areas, the NO_3-N levels in soil water in the vadose zone below the rooting depth can be used as an indicator of potential NO_3-N loading into groundwater.

The European Union (EU) recommended standard for NO_3^- in drinking water is 50 $mg \cdot L^{-1}$ NO_3^- (Tunney, 1992). This critical concentration is based on NO_3^-, which is equivalent to 11.3 $mg \cdot L^{-1}$ NO_3-N, therefore, it is very close to the USEPA drinking water standard of 10 $mg \cdot L^{-1}$ NO_3-N. The EU is forcing all member nations to adopt a policy of reducing NO_3^- pollution of groundwater. As of year 2000, the Netherlands' parliament adopted a policy to restrict groundwater NO_3^- concentration, at 2 m depth, below the EU recommended NO_3^- critical standards for drinking water. As of the year 2002, all farmers in Netherlands are required to submit to the government N balance sheets showing N input and export at the farm level. When averaged on per hectare basis, if the N input exceeds N export, those farms are liable for a penalty. There is often considerable debate on the reliable method for calculation of N and phosphorus (P) inputs and exports at the farm level.

Excess concentration of NO_3-N in drinking water is reported to cause a health disorder called "blue-baby syndrome." This disorder is characterized by shortage of oxygen in tissues where it is needed. As a result, blood loses its characteristic red color and turns into a bluish cast which is the origin of the term "blue-baby syndrome." Some researchers believe that the above disorder is caused by nitrite (NO_2^-) rather than by nitrate (NO_3^-). The former is generally at low amount in the environment, but can be produced from NO_3^- as a result of a microbial reduction process.

The human health risk associated with NO_3-N in drinking water occurs in infants under the age of six months. This is due to the acidity of the gastrointestinal tract in infants is not sufficient to prevent the growth of bacteria which convert nitrate to nitrite. Therefore, for infants a heavy intake of NO_3^- could result in buildup of NO_2^- to toxic levels which could be absorbed into the blood stream. Furthermore, the conversion of hemoglobin into methemoglobin is more rapid in infants than for adults. The intake of fluid per unit body weight basis is greater for infants than that in adults.

NITROGEN UPTAKE EFFICIENCY

Nitrogen is key in maintaining the economic viability of worldwide agricultural systems and feeding the world population. The Food and Agricultural Organization of the U.N. reported that worldwide use of N fertilizer in 2002 was 84.7 million metric tons (www.fao.org/waicent/portal/statistics_en.asp). The N uses in different geographical regions in millions of metric tons were: Africa 2.7; North America 12.5; Latin America 5.0; Asia 49.8; Europe 13.3; and Oceania 1.3. Raun and Johnson (1999) reported a N uptake Efficiency (NUE) for cereals of approximately 33 percent with a total use of 49.7 million metric tons worldwide for these crops. This indicates about 29.8 million metric tons of N applied to cereal crops worldwide is unaccounted, and suggests various losses. Assuming a cost of $ 0.48 per kg N, the economic loss as a result of unaccounted N applied to cereals worldwide amounts to 15.9 billion U.S. dollars (Raun and Johnson, 1999).

Delgado (2002a) reported an annual economical loss equivalent to 26.0 to 36.4 billion U.S. dollars worldwide, assuming the cost of N at $0.66 per kg N, and depending on the range of NUE values for various crops. The economic loss estimates did not include the losses of handling the unaccounted N, or the reduction in yields, or lower crop quality due to lower NUE. The loss of N also results in negative effects on the environment, as discussed in this chapter. It is important to continue developing Best Management Practices (BMPs) that increase NUE and decrease economic losses and potential negative effects on the environment.

In order to improve worldwide NUE for agricultural systems, we need to develop and implement N Management Plans (NMP) within the context of the N cycle, considering that N is the most dynamic and mobile essential nutrient (Delgado et al., 2002). The fate and transport of N are closely related to the major pathways leading to losses from the system (Follett and Delgado, 2002). Ammonia (NH_3) volatilization, emissions of nitrous oxide (N_2O), nitric oxide (NO), oxides of N (NO_x) and dinitrogen (N_2), contribute to atmospheric losses of N. Leaching NO_3-N below the root zone and off site transport with tile drainage can contribute to N losses. Wind and water erosion can contribute to off-site transport of N bound with organic matter and soil particles, and inorganic

NO_3-N and NH_4-N forms. These primary and secondary pathways, including those of the N removed with crop products that are used for human consumption and animal feeding can contribute to further redistribution of N in the biosphere.

Implications of Low Nitrogen Uptake Efficiency

A large proportion of N losses from agricultural systems across several worldwide agroecosystems are correlated with low NUE. These anthropogenic increases in losses from the N cycle have been reported to contribute to gaseous emissions that are contributing to global warming (IPCC, 1994) and increasing trend of greater NO_3-N levels in groundwater resources during the recent years (Follett et al.,1991). We can design studies to quantify the fate and transport of N and to identify BMPs that can increase NUE by decreasing these losses (Delgado, 2001a; 2001b; 2002a). Although weather, land uses, soils, and N inputs are correlated with N losses, management is a key factor in improving NUE (Delgado, 2001a; 2001b; Pate et al., 2001, Shaffer and Delgado, 2002). It is difficult to develop a best management practice that can work under all situations, i.e., one "*silver bullet*" solution. However, a series of tools have been developed that can be used for a set of specific climates, soils, and crops, to improve NUE and reduce losses to the environment (Pate et al., 2001).

To explain N uptake efficiency, it is important to understand various reactions in the soil that influence the fate and transport of N. These reactions are controlled by physical, chemical, and biological factors of soils present in the zone of nitrogen fertilizer application, amount of readily available energy source and amount of water. Associations between microorganisms and plants fix atmospheric nitrogen (N). Subsequent transformations and recycling through organic and inorganic compounds are of interest for sound nutrient management in agricultural systems. For efficient use of applied N by crops, the amount of available water in the rooting depth and root distribution are important. Availability of excess water, soil organic matter, and soil textural and topographic characteristics will play a significant role in determining the rate of various reactions involving the applied N. These include: surface adsorption, surface runoff, deep percolation and leaching, microbial assimilation and immobilization, volatilization, and denitrification. Timing of fertilizer application also plays an important role in determining the efficient use of applied N.

Nitrogen uptake efficiency is generally 40 to 50 percent for cereals (Craswell and Godwin, 1984; Hallberg, 1987) and is much lower for tree crops, where it is about 20 to 40 percent (Dasberg, 1987). Nitrate leaching potential is quite high under potato production systems (Chu et al., 1997; Mohamed et al., 1998). Crop factors, in particular physiological factors that influence the N uptake, as well as magnitude of root distribution, also contribute to NUE and N losses (Delgado 2001a; 2001b). Delgado (2001b) found that for center-pivot irrigated systems the NUE for deeper rooted small grains such as wheat and barley was greater that the NUE of shallower root crops such as potato and lettuce. Detailed discussion of these factors is not within the scope of this publication. Much of the emphasis in this publication is on N dynamics in soils and the relative importance of various physical, chemical and biological transformation processes on the utilization efficiency of applied N. In addition, role of water management in the above processes and influence of water management techniques for mitigating N leaching losses will be discussed. Efficient and environmentally friendly N management requires sound knowledge on the total and patterns of crop needs of N as well as the quantity and pattern of N likely to become available during crop growth. Furthermore, crop N requirements and the release of N from soil organic reserves depend largely on management and climate (Delgado and Follett, 2002). Depending on the type of crop and cultivation pattern, fertilizer application strategy should be devised in such a way as to take all climatic factors into consideration to achieve optimum NUE. These management factors are also very important to minimize the risk of environmental pollution affecting soil, air, and water.

NITROGEN CYCLE AND POTENTIAL PATHWAYS FOR LOSSES

If we are going to increase NUE, we need to do it within the context of the N cycle. For most crops, the product of economic value is a portion of the total biomass production. This ratio is referred to as "Harvest Index." At the end of the normal crop growth cycle, only the product of economic value is harvested and transported away from the cultivable land. Thus, the nutrients in the harvested product are considered as the net removal from the soil plant system. The vegetative portion of the annual crop is generally incorporated into the soil, while that of the perennial crop is partly returned to the soil by leaf senescence or act as storage for the subsequent years production. Therefore, the nutrients in the vegetative portion of the crop is returned to the soil in the case of the annual crops, or partly stored in the woody portion of the perennial crops. Delgado and Follett (2002) defined the nutrient cycling ratios (NCR) as the nutrient content in the vegetative portion of the crop divided over the nutrient content removed from the field. The NCR greater than one indicates a higher potential for cycling nutrients with the crop residue during soil cultivation which can then be released in forms available to the next crop. An NCR lower than one indicates a higher removal of the nutrient with the harvest portion of the crop than the amount that is returned with the crop residue. Delgado and Follett (2002) reported that for small grains the NCR for N and P were lower than one. This is one of the reasons why most soils are deficient in N, since significant quantities of N are removed with the harvested crop relative to what is returned to the soil with the crop residue. The NCR for potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), and boron (B) on average were greater than one indicating a large potential for cycling these macro and micro nutrients.

Delgado and Follett (2002) recommended that carbon management and nutrient cycling be part of nutrient management plans for maintaining the sustainability of the biosphere. They reported that there is potential to use carbon management to reduce NO_3^- leaching if proper credits are given to organic amendments such as crop residues, soil organic matter and manures, and if the release of N is coordinated with the periods of high demands for N by the crop in question. If proper credits are not given, then there is potential to increase NO_3^- leaching as a result of greater N availability than what can be utilized by the crop. If the release of N is not coordinated and a significant amount of N is released after the crop is harvested or at the end of the growing season, there will be increased amount of NO_3^- potentially available to leach (Meisinger et al., 1991). If crop residues or organic wastes with C to N ratios greater than 35 are incorporated, there is N immobilization as the material initially decomposes (Pink et al., 1945, 1948).

The process of N immobilization occurs when inorganic N sources are applied to the soil with large amount of organic matter with high C to N ratios. This process temporarily ties up the readily available N into unavailable forms, thus, could decrease NUE. However, when the conditions are conducive for mineralization, these organic compounds are converted into inorganic N compounds through two-step process thus N is made available to crops. The process of nutrient transformation from organic forms into plant available inorganic forms is referred to as "mineralization." In the case of N, mineralization involves decomposition of organic residue and conversion of organic N into NH_4^+ and NO_3^- forms.

Once inorganic N has appeared in the soil, it can be absorbed by the roots of higher plants or still metabolized by other microorganisms during nitrification. This process is carried out by a specialized series of reactions in which a few species of microorganisms oxidize NH_4^+ to NO_2^- or NO_2^- to NO_3^-. Ammonium ion can also react with excess hydroxyls in soil solution, which leads to N losses to the atmosphere by NH_3 volatilization. This represents an important source of N loss in agricultural soils under favorable conditions. Furthermore, inorganic N is subject to denitrification by microbes that are able to utilize the N in NO_3^- and NO_2^- as terminal electron acceptors. This results in gaseous losses of N compounds such as molecular N_2 or N_2O. Denitrification is favored under anaerobic conditions and in the presence of a soluble carbon source, which is an energy source for denitrifying bacteria.

Due to the extensive use of N fertilizers and nitrogenous wastes, the amount of N available to plants may significantly exceed the N returned to the atmosphere by gaseous losses of N through volatilization and denitrification. A portion of this excess N in the soil is leached out in the soil profile as NO_3^- or carried in runoff waters. These are conducive conditions for N losses in agricultural soils, thus reducing NUE. Additionally, in waterways and neighboring ground-water systems the N concentration could exceed the levels acceptable for human consumption. Furthermore, other processes such as adsorption, fixation, immobilization and microbial assimilation of added NH_4-N in soils are of great importance and that affects NUE and has corresponding environmental repercussions.

Nitrogen Cycling and Mineralization

The N cycle plays an important role in life process. It is in the soil that we find many reactions driving N transformations, which usually involve the oxidation of one compound and the reduction of another accompanied by release of useful energy for microorganism survival. A key part of the N cycle is the mineralization process that recycles plant and animal litter as it decomposes and mixes with the soil. Factors that affect these biogeochemical transformations have been described in detail by several authors (Tisdale and Nelson, 1975; Stevenson, 1982; Hutchinson, 1995). The mineralization process is affected by several factors including soil type, crop residue C to N ratio, lignin and hemicellulose concentrations, climate, and tillage. In summary, heterotrophic organisms drive the aminization and ammonification processes while autotrophic *Nitrosomonas* convert the NH_4^+ to NO_2^- and *Nitrobacter* converts the NO_2^- to NO_3^-. It is in this process of nitrification that NO and N_2O gases can be formed and emitted into the atmosphere (Tortoso and Hutchinson, 1990) (Figure 1).

Organic N occurs in a wide range of compounds in the soil organic matter, which is subject to transformation carried out by the need of heterotrophic microbes for energy and carbon. This process, named ammonification, occurs in several steps and results in the production of NH_4^+. Soil receives NH_4^+ form of N by application of NH_4^+ sources of fertilizers or following the conversion of urea into NH_4^+ form when using urea. Ammonium can be absorbed by the plant roots or it can be metabolized by other microorganisms during nitrification.

Mineralization and N cycling have been studied under several *in situ* techniques or with laboratory incubations of soils at optimum water, temperature, and incubation time (Stanford and Smith, 1972). The in-situ method in general is preferred since it incorporates the field conditions that impact the mineralization. Dou et al. (1997) used the soil column incubation technique for determining the N mineralized in soil under the canopy of 4- and 20-year old ‘Hamlin’ orange trees on ‘Cleopatra mandarin’ grown on a Tavares fine sand (hyperthermic, uncoated Typic Quartzipsamment), and 7- and 40-year old ‘Temple orange’ trees on ‘Sour orange’ rootstock grown on a Wabasso sand (sandy, siliceous, hyperthermic Alfic Haplaquod). Nitrogen mineralization was measured at 0 to 15 and 15 to 30 cm depth soil by installation of PVC column. The initial status of NO_3-N and NH_4-N was measured by analysis of the soil samples taken adjacent to the incubation column. At the end of the incubation period, the column was excavated to measure the extractable NH_4-N and NO_3-N concentrations. The amount of N mineralized was calculated by the difference between the initial status and that at the end of the incubation period. This process was repeated to estimate the N mineralization on an annual basis. The plant residue samples were also collected at the two depths for dry matter measurement. The concentration of N in the plant residue was measured to calculate the amount of total N in the residue on an area basis. This provides an estimate of potentially mineralizable N (PMN).

Two years data showed that annual N mineralization from tree residue varied from 58 to 84 and 126 to 153 $kg \cdot ha^{-1}$ for 4- and 20-year old ‘Hamlin’ orange trees, respectively (Figure 2). The amount of N miner-

FIGURE 1. Effects of soil water content on the microbial activity and optimal soil water content for nitrification (a) and denitrification (b) reactions (data from Tortoso and Hutchinson, 1990 and Mosier et al., 2002).

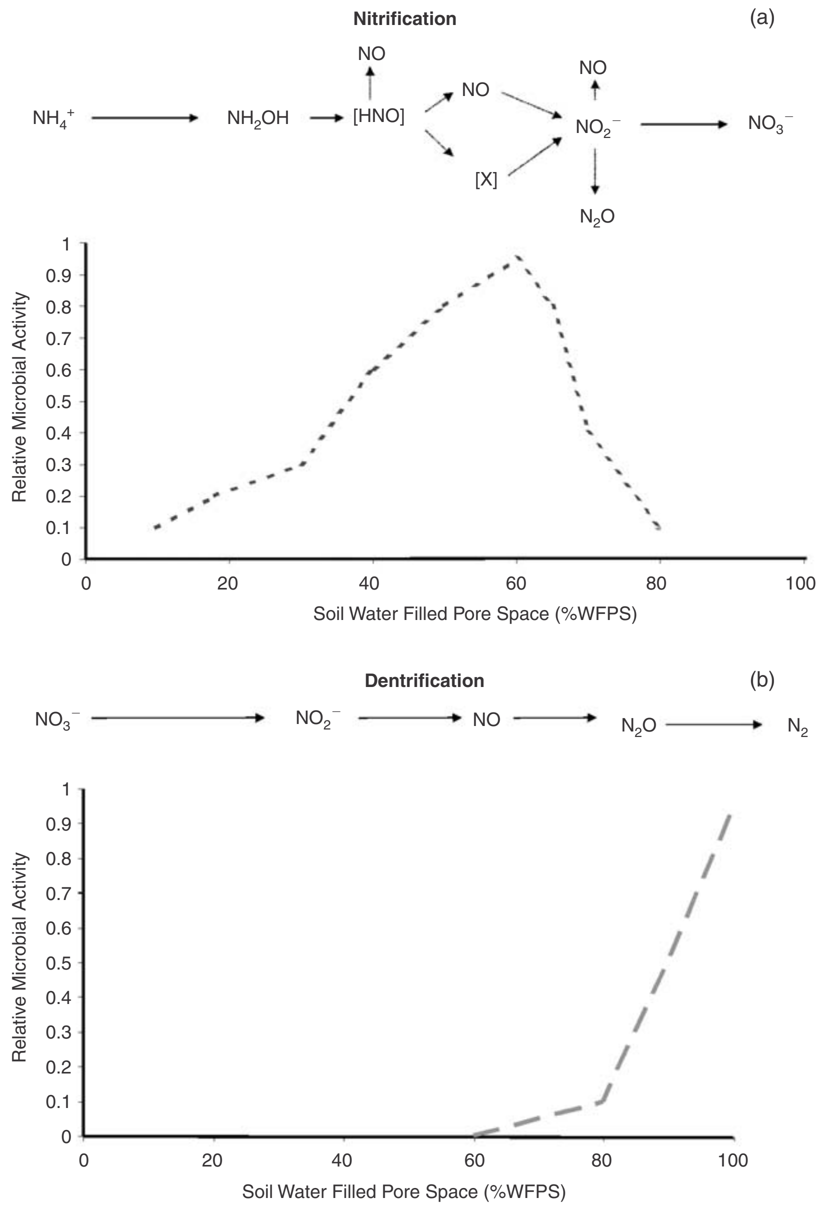
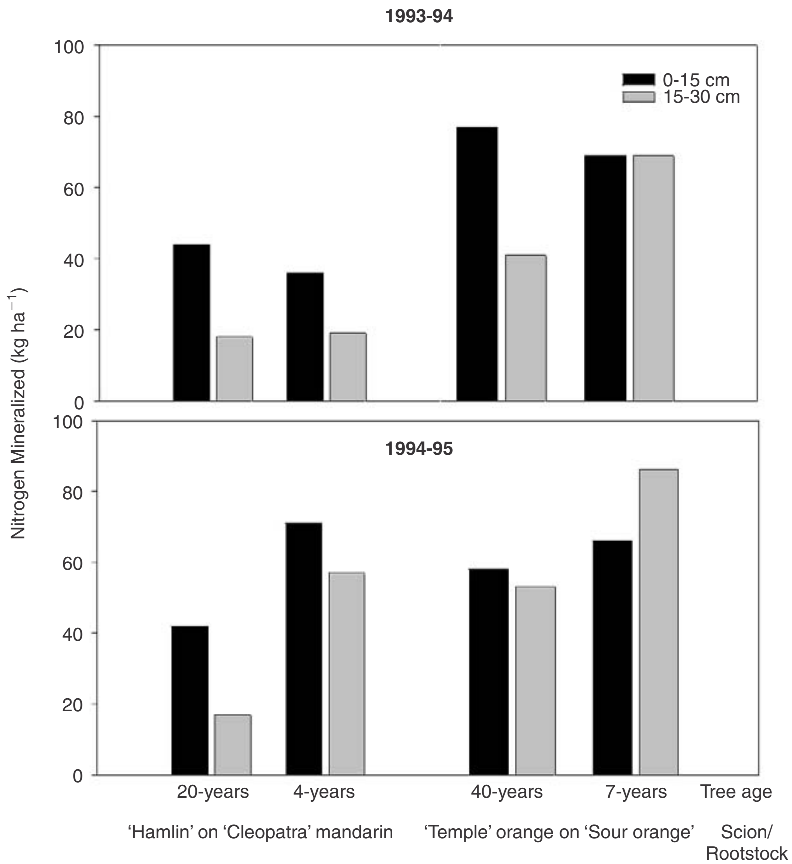


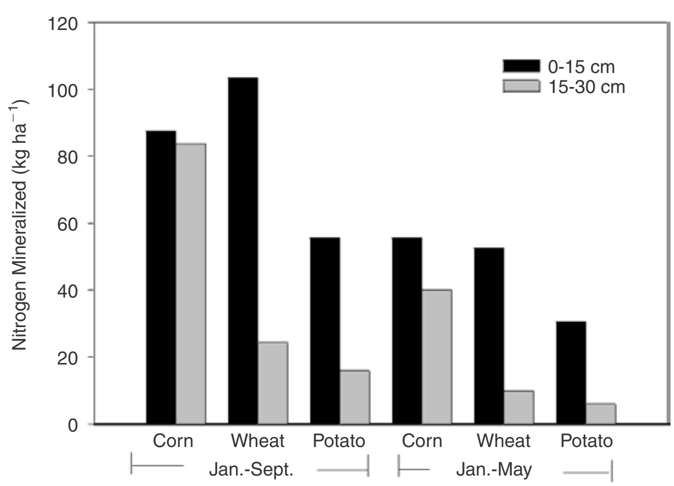
FIGURE 2. Nitrogen mineralized over two year period under the tree canopy of 4, and 20 year old Hamlin orange trees on 'Cleopatra mandarin' rootstock, and 7 and 40 year old Temple orange trees on 'Sour orange' trees (data from Dou et al., 1997).



alized in the case of 'Temple orange' trees was somewhat lower than that for the 'Hamlin' orange trees. In the case of the former, two year data showed a range of 36 to 64 and 121 to 126 kg·ha^{-1} for the 7- and 40-year old trees, respectively. The measured quantities of N mineralized on an annual basis accounted for 36 to 71 percent and 42 to 44 percent of PMN for the 4- and 20-year old 'Hamlin' orange trees, respectively, on Tavares fine sand. In the case of the Wabasso sand, the annual quantity of N mineralized accounted for 66 to 69 percent and 58 to 77 percent of PMN for the 7- and 40-year old 'Temple orange' trees, respectively. The latter soil is of somewhat heavier texture with slightly greater water holding capacity as compared to that of the Tavares fine sand. This could explain the greater percent mineralization in the Wabasso sand as compared to that in the Tavares fine sand. The study also showed that much of the N mineralization occurred in the surface 15 cm soil.

A similar in-situ incubation technique is used to measure N mineralization in row crops under irrigated potato rotation system in the Pacific Northwest (Alva et al., 2002). Potato in this region is grown on a 3 to 4 year rotation with field corn, wheat, and occasionally, with alfalfa. Results of January through September measurements are shown for potato, corn, and wheat residues in the preceding year. Total N mineralized during this period was 172, 128, and 72 kg·ha^{-1} for corn, wheat, and potato residues (Figure 3). Data are also shown for January through May period for the respective residues. This period represents either no N uptake or negligible N uptake because of limited crop growth, immediately after planting until the stand establishment. Significant quantity of N mineralized during this period is of concern with respect to NO_3-N leaching below the rooting zone of the subsequent crop in rotation.

FIGURE 3. Nitrogen mineralized from crop residues in a typical potato-wheat-corn rotation in an irrigated Pacific Northwest production region with sandy soil (data from Alva et al., 2002).



Nitrification

Nitrification is a two-step process of oxidation of NH_4^+ to NO_3^-, which is mediated mostly by chemoautotrophic microorganisms and takes place in soils under warm temperature, neutral pH, and aerobic conditions. This process includes a series of reactions in which a few species of microorganisms oxidize the NH_4^+ to NO_2^- and then to NO_3^-. Heterotrophic nitrification is carried out by few species of fungi and bacteria and does not involve gain of energy for microbial growth and rates.

Few bacterial genera of chemoautotrophic nitrifiers are being identified in the soil (Myrold, 1998). Carbon source for microbial growth and activity is derived from dissolved HCO_3^- in the soil solution and the process is regulated by the amount of NH_4^+ available to the microbial population. Microorganisms of the genus *Nitrosomonas* oxidize the ammonium ion as their energy source. In the presence of oxygen, NH_4^+ is converted to NO_2^- (Reaction III-1). There is another specialized group of microorganisms, represented by *Nitrobacter*, are capable of extracting energy by oxidizing NO_2^- into NO_3^- (Reaction III-2). Ammonium is in equilibrium with NH_3 in soil solution. Therefore, the two-step process may be described as follows (Schmidt, 1982):

$$NH_4^+ + 1\ 1/2\ O_2 \rightarrow NO_2^- + 2H^+ + H_2O \qquad -65\ \text{kcal mol}^{-1} \qquad \text{(III-1)}$$

$$NO_2^- + 1/2\ O_2 \rightarrow NO_3^- \qquad -17.8\ \text{kcal mol}^{-1} \qquad \text{(III-2)}$$

Inorganic-N oxidizing bacteria have also been found in acid soils, even though nitrification rates are higher at neutral pH. De Boer et al. (1995) described that formation of microcolonies is essential for *Nitrosospira* bacteria to have nitrifying activity at low pH and that, after a period of pH fluctuation, they adapt to acid conditions. Thus, *Nitrosospira* spp may be involved in the oxidation of NH_4^+ at a low soil pH, even though they appear to be acid-sensitive after isolation. Accumulation of NO_2^- to detectable levels in the soil is not common since reaction II occurs at higher rates than reaction I. Under conditions of high NH_3 concentration, where NH_3- or NH_4-forming fertilizers are applied to alkaline soils oxidation of NO_2^- to NO_3^- by *Nitrobacter* may be inhibited by toxicity of free NH_3 (Chapman and Liebig, 1952).

Transformation of either urea or ammonium form of N into nitrate form is quite rapid (Khakural and Alva, 1995; 1996). Khakural and Alva (1995, 1996) reported the rapid transformation (within 4-7 days) of

NH_4^+ to NO_3^-in soils of Florida during the summer months. This process transforms a cation N form into an anion form (NO_3-N) which is poorly retained in the soil, therefore, subject to leaching losses through the soil profile and eventually into groundwater. Therefore, NO_3^- leaching losses can be a significant concern under conditions that favor rapid transformation of NH_4^+ into NO_3^-, despite using NH_4^+ source of N fertilizers. An important characteristic of reaction III-1 is that nitrification of mole of NH_4^+ produces 2 moles of H^+. Therefore, acidification of soil is increased with application of NH_4^+ form of fertilizers (Table 1). Lowering soil pH results in losses of basic cations accompanied by leaching of NO_3^- with consequent decrease in soil base saturation. He et al. (1999) demonstrated an increase in leaching of PO_4-P, Ca, and K below the rootzone of grapefruit trees in a sandy soil of Florida with a

TABLE 1. Soil acidification and cation losses 5 years after first application of different rates of nitrogen as urea or ammonium nitrate (AN).

Application rate	pH ($CaCl_2$)		$Ca^{2+} + Mg^{2+} + K^+$		Soil base saturation	
	Urea	AN	Urea	AN	Urea	AN
	-- kg ha^{-1} N --		-- mmol$_c$ dm^{-3} --		-------- Percent -------	
Sampling depth 0-20 cm						
20	5.6a†	5.8a	47b	64a	67a	77a
100	5.5a	4.9b	40a	40a	65a	51a
180	4.9a	4.4b	45a	28b	58a	38b
260	4.7a	4.1b	33a	19b	47a	24b
Rate effect‡	L	L	L	L	L	L
Sampling depth 20-40 cm						
20	5.3a	5.6a	27a	36a	55b	68a
100	5.8a	5.3b	35a	37a	69a	64a
180	5.5a	5.1a	40a	32a	67a	59a
260	5.3a	4.8b	33a	27a	62a	48b
Rate effect	ns	L	ns	ns	ns	L
Sampling depth 40-60 cm						
20	5.5a	5.7a	32a	33a	65a	66a
100	5.7a	5.4a	37a	31a	67a	61a
180	5.4a	5.6a	36a	35a	63a	65a
260	5.4a	5.4a	27a	28a	57a	59a
Rate effect	ns	ns	ns	ns	ns	ns

† Means followed by the same letter, comparing N sources with same application rate (paired values in the line) are not significantly different (Tukey $P \leq 0.05$).
‡ L and ns: linear and non-significant effect of rates of N application ($P \leq 0.05$) in the column.
Adapted from Cantarella et al., 2003.

decrease in soil pH by 0.7 to 1.7 units after application of 112 kg $N \cdot ha^{-1}$ for four years. The use of nitrification inhibitors has been studied for decades to slow the process of nitrification thereby prolonging retention of N in NH_4^+ form (Delgado and Mosier, 1996). This is expected to minimize NO_3^- leaching losses and increase efficient use of N fertilizer by plants and minimize adverse environmental impacts caused mostly by NO_3^- leaching. Several molecules, i.e., pyridines, thiazoles, and nitrapyrin, were tested and commercial products were released in the market (Myrold, 1998).

Denitrification

Denitrification is an important process of the N cycle because it is the primary mechanism for the return of N_2 to the atmosphere (Hutchinson, 1995). It is most controlled by the supply of oxygen (O_2), the concentration of NO_3^-, and the amount of available C in the soil for microbial growth. There are numerous kinds of denitrifying bacteria, most represented by the genera *Pseudomonas*, *Alcaligenes* and *Flavobacterium*, fungi, and algae (Myrold, 1998). In the absence of oxygen, denitrifying bacteria are able to use the NO_2^- or NO_3^- ion as alternate electron acceptors for oxidation of organic compounds and energy yield via oxidative phosphorylation. Nitrate form of N can be subject to denitrification by microbes that are able to utilize the N in NO_3^- and NO_2^- as terminal electron acceptors. This results in gaseous losses of N either as N_2 or as nitrous oxides (N_2O).

Denitrification does not proceed to any great extent under aerobic conditions (Figure 1). This process is driven by several factors including the availability of suitable reductants, restriction of O_2 availability, and availability of N oxides, NO_3^-, NO, or N_2O (Firestone and Davidson, 1989; Hutchinson, 1995). Peoples et al. (1995) reported that for poorly drained clay soils the denitrification potential was seven-fold greater than that of the well drained sandy soils. Many denitrifiers are facultative, therefore whenever O_2 is available, it is energetically advantageous for an organism to use it to oxidize organic compounds rather than to use the oxygen of inorganic-N. Additionally, synthesis and activity of nitrate reductase, a common enzyme to denitrifiers that catalyzes the reduction of NO_3^- to NO_2^-, is inhibited by free oxygen (Drury et al., 1991). Nitrifying microorganisms of the genus *Nitrosomonas* were also found to contribute to emissions of N_2O from aerobic soils during oxidation of NH_4^+ to NO_3^- (Bremner, 1997).

Volatilization

Volatilization of NH_3 is a result of chemical reactions in the soil and which markedly contributes to gaseous losses of N under favorable conditions in agricultural systems. Several authors have reviewed the factors that affect NH_3 volatilization from agricultural systems (Fox et al., 1996; Freney et al., 1981; Stevenson, 1982, Sharpe and Harper, 1995; Wood et al., 2000). Volatilization of NH_3 is affected by soil pH, especially as soil pH exceeds 7.0. This process is dependent on the chemical equilibrium between concentrations of NH_3 and NH_4^+ in the soil solution, which is regulated by the soil pH. In pure solutions, the above reactions can be described by equations III-3 and III-4. The dissociation constant of equation III-3, expressed as p*Ka*, is 9.3 (Havlin et al., 1999). Therefore, volatilization of NH_3 can be significant following the application of NH_4^+ forming fertilizers in high pH soils.

$$NH_4^+ \leftrightarrow NH_3(aq) + H^+ \tag{III-3}$$

$$NH_3(aq) \rightarrow NH_3(air) \tag{III-4}$$

Urea is the most common N fertilizer used for various crops around the world. Widespread use of urea is due to its high N content, which decreases the cost of manufacturing, handling, storage, transportation, and its application on a per unit N basis. However, NUE from urea is generally lower than that for other N sources because, in part, volatilization of NH_3. Gaseous losses of NH_3 from soil following urea fertilizer application may account up to 75 percent of total N applied in some extreme conditions (Cantarella et al., 2003; Mattos, Jr. et al., 2003; Fenn and Miyamoto, 1981). The general process of NH_3 volatilization from applied urea is related to a localized increase in soil pH after dissolution and hydrolysis of the fertilizer (Hauck, 1984) as described in equations III-5 and III-6.

$$(NH_2)_2CO + H^+ \rightarrow HCO_3^- + 2\,NH_4^+ \tag{III-5}$$

$$HCO_3^- + H^+ \leftrightarrow CO_2 + H_2O \tag{III-6}$$

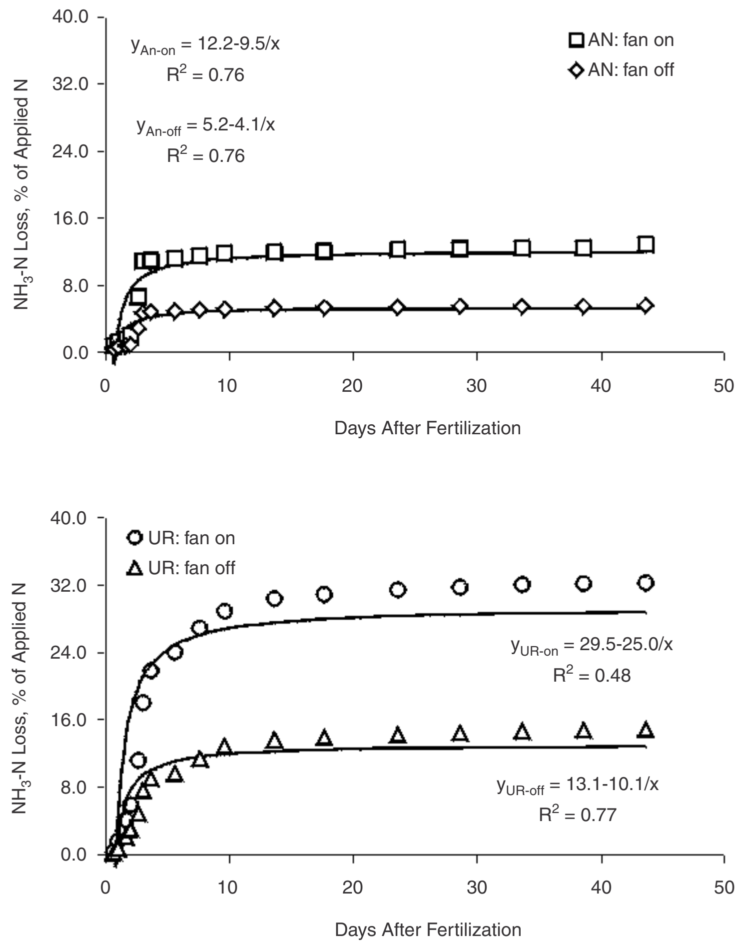
The hydrolysis of urea is completed within days after soil application (Yadav et al., 1987; Khakural and Alva, 1996). The reaction is catalyzed by enzymes of the aminohydrolases group present in the soil of which urease is one of the most important (Tabatabai, 1994). Its presence in soil is related to a large number of bacteria, fungi, and actinomycetes (Myrold, 1998). Urease is common in soils and its activity is a function of substrate concentration (Singh and Nye, 1984) and soil properties, like temperature (Voss, 1984), pH, moisture, texture, buffer capacity and organic C content (Bremner and Mulvaney, 1978). Greatest activity of urease is also related to rhizosphere region, where microbial activity is high and organic C is available in abundance as plant root exudates. The rate and extent of NH_3 volatilization are favored by increased soil carbonate content, rate of applied NH_4-N (Fenn and Kissell, 1974), temperature (Mattos Jr. et al., 2003), availability of water in the soil system during wetting and drying cycles (Freney et al., 1992a), and wind speed. The influence of wind speed is due to its affects on NH_3 vapor pressure gradient at the soil to atmosphere interface (Figure 4).

Application of greater rates of N fertilizers to the soil surface enhances volatilization losses because overlapping of fertilizer granules increases NH_4^+ concentration in microsites of soils (Figure 5). An increase in soil pH depends, in part, on the degree of urea-fertilizer diffusing in the microsites (Black et al., 1985). Volatilization of NH_3 is more significant when fertilizers are applied to the soil surface covered with plant material (Urban et al., 1987). Increased NH_3 volatilization losses in plant residue mulched soils are due to the affects of residues: (i) forming a physical barrier between the N source and the soil, (ii) minimizing drying of surface soil, and (iii) providing additional source of urease enzyme.

Runoff of N into Surface Water

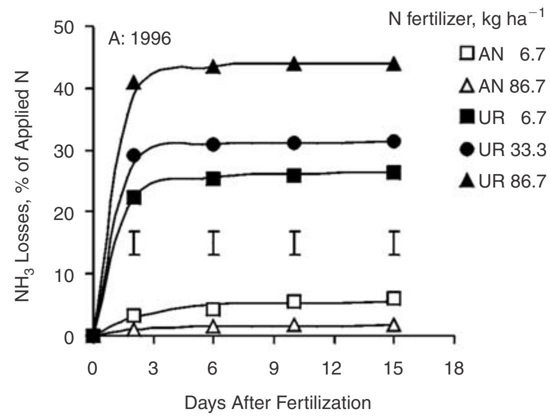
Two main mechanisms for off-site transport of N are water erosion predominantly in humid systems and wind erosion in drier systems. Wind erosive forces can contribute to the transport of N attached to soil particles or tied up in the soil organic matter (SOM) (Woodruff and Siddoway, 1965; Bilbro, 1991; Delgado et al., 1999; 2001). This N can be transported for long distances before being deposited or contaminating bodies of water. Legg and Meisinger (1982) estimated the wind and water erosion losses of N in the U.S. at 0.9 and 3.6 million metric tons, respectively. The above losses were equivalent to 0.6 and 2.4 billion U.S. dollars, respectively (Delgado 2002a). Soil and water conservation practices are key to reducing the potential N losses due to wind and water erosion. Holt (1979) reported that residue management can be used to reduce wind and water off-site transport of N. Minimum tillage can

FIGURE 4. Ammonia volatilization measured by a semi-open collector system from field fertilized with ammonium nitrate (AN) or urea (UR). Ammonia collector system set with (fan on) and without (fan off) additional air circulation (data from Mattos Jr., et al., 2003).



reduce water transport of N, with lower losses than those measured for the chisel plow and conventional tillage (Seta et al., 1993). Dabney et al. (2001) reported that winter cover crops (WCC) can reduce wind and water erosion, and conserve soil and water quality. Lentz and Sojka (1994) reported that application of polyacrylamide (PAM) to furrow

FIGURE 5. Cumulative NH_3 volatilization as percentage of surface applied N in different rates and forms. Vertical bars indicate the least significance difference (LSD; $P \leq 0.05$) for NH_3 volatilization within time. AN: ammonium nitrate; UR: urea. Numbers following symbols refer to rate of N application in kg ha^{-1} (data from Cantarella et al., 2003).



irrigation treatments significantly reduced sediment in runoff by 94 percent.

Removal of nutrients from their sources such as fertilizers, animal manures, and organic wastes attached onto soil and sediment particles transport by surface runoff water is a major cause of declining productivity of many arable soils and to a decrease of NUE. To remove fertilizer N by such means, an erosive event must occur soon after fertilizer application but before fertilizer N is taken up by the plants. This process not only results in losses of nutrients but also contributes polluting natural waterways such as streams, aquifers, and water storages. Surface runoff and water erosion are very common in lands with steep slope, shallow depth, and physically or chemically unfavorable subsoil and ultimately result in loss of nutrients, contamination of surface water bodies and decrease nutrient uptake efficiency. Catchment studies (Burwell et al., 1975; Alberts et al., 1981) have shown that the majority of N is transported in the solid phase by attachment to soil particles, with only small amounts moving in the solution phase. In contrast, application of N fertilizers to soils deficient in N may reduce soil erosion by enhancing the growth of vegetation which protects the soil erosion during excess rainfall (Loch and Donnollan, 1988). This is universally accepted conservation practice to combat soil erosion and nutrient loss. There are some other cultivation practices such as step and contour cultivation, increasing soil organic matter by planting grasses or cover crops also practiced various part of world to control surface erosion and nutrient losses.

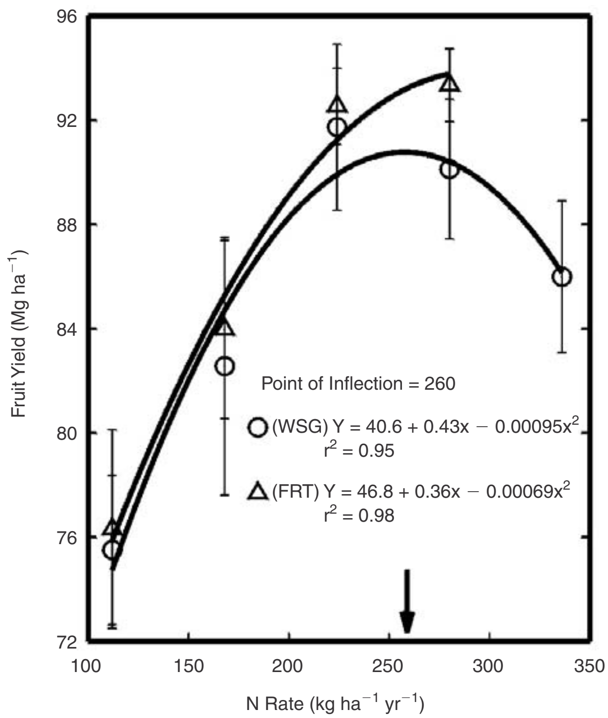
Nitrate Leaching into Ground Water

Land use patterns have been correlated with underground water NO_3-N concentrations (Hallberg, 1989; Fletcher, 1991; Juergens-Gschwind, 1989). Shaffer and Delgado (2002) proposed the development of a U.S. national NO_3-N leaching index to identify sensitive areas that are potentially susceptible to NO_3-N leaching. Although in some agricultural areas it is almost impossible to eliminate NO_3-N leaching due to irrigation and precipitation events (Pratt, 1979), application of BMPs for N fertilization and irrigation in most geographical areas can minimize NO_3-N leaching losses (Delgado, 2001a; Shaffer and Delgado, 2002; Schepers et al., 1995). Shaffer and Delgado (2002) and Delgado (2001b) recognized that while weather, soils and off-site factors could drive NO_3-N leaching, management is a key component that can be used to reduce the net losses of NO_3-N from a cropping system.

Nitrate in soil profile may be leached into groundwater when percolating water moves below the rooting depths of crop under consideration. The amount of water in excess of crop requirements and which percolates below the root zone provides the leaching potential within any system. It has been reported that significant leaching of nitrate may also occur in arid regions and in sandy soils (Campbell et al., 1984; Dalal, 1989; Paramasivam et al., 2000a; 2000b; 2001; and 2002), due to episodic periods when total water input (precipitation plus irrigation) exceed evapotranspiration (Meisinger and Delgado, 2002). As an example, a graphical representation of various water balance components computed for mature bearing citrus grown under sandy soils during 1997 cropping year is presented in Figure 6 (Paramasivam et al., 2002). Careful computation of various water balance components in any cropping system would provide a very clear idea about the potential N leaching losses. Losses of N by leaching, like losses due to denitrification, are site specific, being affected by local differences in rainfall, soil water holding capacity, soil drainage properties, and rates of mineralization-nitrification of soil organic N (Delgado, 1999).

Another important factor that determines NO_3^- leaching is the amount of fertilizer N available in excess of crop requirement. Numerous studies indicated a positive relationship between the amount of available N

FIGURE 6. Mean fruit yield of 'Hamlin' orange trees on 'Cleopatra mandarin' rootstock grown in a Tavares fine sand (1995-1998). The data shown are for broadcast application of water soluble granular (WSG; open cirlces) form in four doses per year, and fertigation (FRT; open triangles) in 15 doses per year.



in excess of crop requirement (amount of N available for leaching) vs. nitrate leaching beyond rooting depth (Broadbent and Carlton, 1978; Alva and Paramasivam, 1998; Alva et al., 1998; Paramasivam et al., 2001; 2002). Paramasivam et al. (2001) found a linear relationship between the amount of NO_3-N leached and the amount of N applied using various fertilizer sources (Table 2). Leaching of N from the rooting zone leads to decreased availability of N for plant uptake, thus low NUE.

Amount of available N within the rooting depth at a particular time could be controlled by the selection of N fertilizer rates and sources and by application timing. In citrus crop production, water-soluble dry granular fertilizers, liquid fertilizers, and controlled release fertilizers were

TABLE 2. Effects of N sources and rates on the estimated NO_3-N leached below the rooting depth of mature citrus trees grown in an Entisol with optimal irrigation scheduling in Florida, USA (reprinted with permission from Paramasivam et al., 2001).

Treatments		Year	
N Source†	N rate	1994	1995
	kg ha^{-1} yr^{-1}	-------------- kg NO_3-N ------------------	
WSG	112	10.3	12.4
	168	11.5	13.2
	224	14.0	13.7
	280	22.6	21.3
Regression		‡$y = 25.2-0.22x + 0.0008x^2$	$y = 27.2-0.20x + 0.0007x^2$
		$r^2 = 0.97^*$	$r^2 = 0.91^*$
FRT	112	16.3	18.2
	168	18.4	24.1
	224	23.4	30.4
	280	29.3	35.1
Regression		$y = 20.9-0.09x + 0.0005x^2$	$y = 6.4-0.10x + 0.0001x^2$
		$r^2 = 0.99^*$	$r^2 = 0.99^*$
SRF	56	0.6	0.9
	112	1.1	3.3
	168	3.3	7.9
Regression		$y = 1.8-0.04x + 0.0003x^2$	$y = 1.1-0.03x + 0.0002x^2$
		$r^2 = 0.99^*$	$r^2 = 0.99^*$

* Significant at $P = 0.05$.
†Four rates (WSG and FRT) and three rates (SRF) of N sources were analyzed separately for each cropping year for statistical significance and for further regression analysis.
‡ Regression equations showing relationship between estimated NO_3-N leached (y) vs. N rates (x)

used. Most of the citrus growing areas of Florida are on sandy soils and receiving unevenly distributed annual rainfall. Selection of fertilizer source and timing of fertilizer application plays a significant role in efficient use of applied fertilizer by citrus crop and in reducing the N leaching losses. Detailed discussion on development of citrus N BMP is included in the chapter under case studies. Multiple application of annual N rates (examples: 3-4 splits of water-soluble granular fertilizer and about 15-18 split applications of liquid fertilizer via irrigation system, and avoiding fertilizer application during heavy rainfall period of mid-May to September, along with careful irrigation scheduling to replenish the water deficit within the active rooting zone are recommended to increase N uptake efficiency and reduce NO_3-N leaching losses (Alva and Paramasivam, 1998; Alva et al., 1998; Paramasivam et al., 2000b; 2001; 2002).

Adsorption and Fixation

Surface adsorption of applied NH_4-N is a common phenomenon generally demonstrated by several researchers in soils that have high cation exchange capacity manifested by greater negative charges on their surfaces. Fixation of applied NH_4-N is well documented in soils, which are rich in three layer or 2:1, type clay minerals. In general, the capacity of 2:1 clay minerals to fix applied NH_4-N appears to be determined partly by the location of the negative charge from isomorphous substitution within the clay lattice. Extensive research studies have demonstrated that clay minerals can fix agronomically significant quantities of applied NH_4-N. Likewise, it has been demonstrated in both greenhouse and field studies that a significant amount of the fixed NH_4-N can be released to the crop later in the growing season or to subsequent crop. A study by Hargove and Kissel (1979) on a Houston black clay calcareous soil in central Texas illustrated how fixation of applied N fertilizers may reduce NUE in one year, but the fixed N may be released to the crop in following year. Similarly, Rechcigl et al. (1988) demonstrated the release and contribution of fixed NH_4-N existed in soil as residual N to the crop during the absence of fertilizer application. Therefore, depending on the circumstances, fixation of applied NH_4-N can either have a beneficial effect by serving as a slow release reservoir of N and reducing N losses by leaching, volatilization, or denitrification or it can reduce the N uptake efficiency by fixing applied N that is needed by the crop. However, in the short term, fixation process decrease N availability for plant uptake. Excellent reviews on this subject area have been published by Nommik and Vahtras (1982) and Kissel et al. (2004).

IRRIGATION AND NITROGEN MANAGEMENT

Improving the N management alone will not effectively reduce N leaching on irrigated sandy soils. Excess water from either irrigation or precipitation can cause NO_3^- to move below the root zone. The downward movement of soil applied agrochemicals not being utilized by the crop and/or not adsorbed by the clay particles or soil organic matter, is dependent on the water movement. The amount of water, rainfall and/or irrigation is critical in determining the rapidity with which the chemical can migrate down the soil profile. Therefore, careful management of irrigation to minimize the transport of water below the rootzone is important to minimize leaching of the chemicals and nutrients. This requires that depth of wetting at each irrigation be restricted to the depth of rooting, so that the pollutants including NO_3^-, is kept within the rooting depth. This will also facilitate uptake of nitrate by the roots, thereby, minimize potential leaching losses below the rootzone. Irrigation scheduling should also be based on some measurement of depletion of available soil moisture in the rootzone.

There are several methods of accurately scheduling irrigation water for different crops. All methods require a knowledge of soil water-holding capacity and an estimation of the available soil moisture at any time during the growing season. Soil tensiometers, which measure the tension with which water is held, are excellent tools on sandy soils for determining when to irrigate. The water-balance approach to irrigation scheduling is also a very good method. This method requires the estimation of crop water use. This is a combination of transpiration loss of water from the plants and evaporation from the soil surface under the plant canopy, thus, termed as evapotranspiration. Computerized programs using the water-balance approach to irrigation scheduling are available. It is when we have good water management that we could use several nutrient management techniques that can maximize yield and N use efficiency.

Meisinger and Delgado (2002) discussed water management tools and strategies that can be used to reduce NO_3-N leaching. The hydraulic properties of every system must be accounted. An example would be water-holding capacity. Soil water content before and after every irrigation should be monitored. To minimize water passing through the root zone, precipitation and potential evapotranspiration need to be considered while scheduling irrigation for a given crop under a specific production condition in order to increase water and N uptake efficiencies.

Impact of Temporal Distribution of Rainfall on Water and Nitrogen Management

The total water balance on a regional basis does not give a clear idea on the potential of N losses as a result of excess water input. For an example, average annual rainfall in major citrus production region of Florida is 1350 mm, which is 10 percent greater than the annual potential evapotranspiration of 1200 mm. However, the annual rainfall is a poor indicator of water available for crop requirement. This could underestimate the leaching losses of water as well as N. Sixty percent of Florida's annual rainfall occurs during the summer months (mid-June to mid-September). The poor distribution of annual rainfall, and the high temperature condition in summer require irrigation for optimal fruit production and quality. Most of the soils in the major citrus production regions have low water holding capacity due to high sand content which is greater than 96 percent, low cation exchange capacities, and low organic matter content.

Although Florida receives large amount of rainfall, poor distribution and unusually excess rainfall during some months result in leaching losses during some part of the year while inadequate water availability during the rest of the year. Therefore, irrigation is required during much of the growing season for optimal yield and quality of crop products. The interaction of irrigation and fertilization is important for optimizing water and nutrient uptake efficiency, and minimizing the negative effects on water quality. Studies on N best management practices (BMPs) for Florida citrus on sandy soils conducted in the 1990s have increased our understanding on managing water and nutrients. These studies became the basis for new recommendations on optimal fertilization and irrigation for citrus to minimize NO_3^- loading into groundwater, while maintaining profitable production of high quality fruits. Successful N BMPs focus on timing and frequency of fertilizer application and irrigation management. Increased frequency of application of the annual N rate, preferably using fertigation technique, combined with optimum irrigation are the basis of a successful N BMP program under Florida soil and weather conditions. The amount of N application during heavy rainfall months, June through September, must be kept to minimum to overcome the risk of NO_3^- leaching.

Crop N and water requirements vary through the growing season as a result of weather conditions and crop requirements. Usually, N demand is high during active vegetative growth; however, crop water requirement is greater during summer periods and during flowering and fruit setting stages. Maximum crop growth and yield are achieved by following optimum fertilization and irrigation recommendations. In the past decades considerable research has been done on several crops to develop irrigation and fertilizer BMPs. Increased adoption of low volume irrigation methods, such as sprinkler and drip irrigation, and improvements in fertilizer formulations have enabled application of fertilizer and water in precise quantities in multiple applications without affecting the cost of application.

Irrigation Methods

Irrigation methods can be grouped into three different categories, gravity, sprinkler and drip irrigation. Although the surface irrigation methods have low water delivery efficiency, the vast majority of irrigated lands throughout the world are irrigated by some methods of surface irrigations. Drip irrigation method is being adapted extensively as water resources are becoming scarce in many agricultural production regions around the world.

Surface Irrigation

This is the oldest irrigation method used. There are many variations of this irrigation method, which can be classified into three main groups: (i) Basin flooding: A small basin is constructed in irrigated field to allow the water to be applied to an individual basin from either an adjacent basin or from a supply ditch. Leveling is crucial in the success of this method. This method wets an entire land surface at each irrigation event. (ii) Furrow irrigation: This method wets only a portion of the field surface, and provides better control on the flow of water than the first method. Furrow irrigation is better suited for row crops, i.e., potato, cotton, etc. (iii) Flood irrigation: In this method soil between borders is flooded. It is usually practiced on relatively shallow soils. Shock et al. (1992) found that mechanical furrow mulching sugarbeets improved irrigation efficiency, increased the beet yield by 56 $Mg \cdot ha^{-1}$ and recoverable sugar by 970 $kg \cdot ha^{-1}$. It also decreased the loss of sediment from 172 to 15 $Mg \cdot ha^{-1}$, decreased estimated total P loss from 150 to 13 $kg \cdot ha^{-1}$, and decreased total estimated N loss from 374 to 84 $kg \cdot ha^{-1}$. Most N losses were in the form of organic N, and most P losses were in the form of insoluble P in the sediment.

Sprinkler Irrigation

In this method, water is applied to the soil surface as spray to mimic natural rainfall. This method is highly desirable for light textured soils on steep slopes. On these soils furrow or basin irrigation could result in excessive surface runoff leading to soil erosion and poor infiltration. Sprinkler irrigation also provides some frost protection as has been demonstrated on cranberry bogs, blueberries, strawberries, almonds, citrus, vegetables, fruits, and flowers (Hansen et al., 1980).

Irrigation plays a significant role in the fate of N applied in various forms. Research results pertaining to the fate of fertilizers and pesticides applied to turfgrass have shown that leaching of N and pesticides is highly influenced by soil texture, nutrient source, rate and timing of application, and amount of rainfall or irrigation (Petrovic, 1990, and

Balogh and Walker, 1992). Joo et al. (1992) investigated the volatilization of nitrogen-15 labeled urea when applied to turfgrass. They found that when irrigation did not follow the liquid urea application, 50 percent of the urea volatilized within 7 days after the urea application. However, Starrett et al., (1994) showed that less than one percent of the applied urea volatilized when a liquid urea application was followed with irrigation. Studying the fate of N and P, Starrett and Christians (1995) reported that excess irrigation increased N transport compared to a light irrigation and that macropores may play a major role in transport of surface-applied N through soil profiles. Further volatilization of liquid urea was less than 3 percent when followed with irrigation and is reduced to less than one percent under a heavy irrigation. When excess N was applied, both the amount and percentage of N losses increased. Nitrogen leaching losses can be greatly reduced by increasing the frequency of irrigation and fertilization. Increased frequency of N applications at low doses effectively decreased N losses. The efficacy and utilization of N by crops will be limited by the availability of water particularly on light textured soils in dry regions. Rahn et al. (1996) demonstrated that the early growth benefits of starter fertilizer in broccoli crops on sandy soils can be limited under inadequate water supply. In dry regions, the introduction of fertigation through trickle irrigation improves the utilization of N and water (Scaife and Bar Yosef, 1995).

Drip Irrigation

This irrigation method aims at watering the crops frequently with low volume approaching consumptive use of the crops. If designed correctly and used properly, drip irrigation is one of the most efficient irrigation method that minimizes deep percolation, runoff and evaporation losses. A number of experiments with apple trees on relatively shallow soils (Evans and Probesting, 1985) have shown that even though water is applied at rates sufficient to meet the tree demand, leaf water potential is lower than that observed on trees under full coverage irrigation. The mild stress, attributed to higher rootzone resistance due to the limited wetting, induced higher soluble solids in the fruits, early flowering in young trees, and sometimes, higher cumulative apple yields in the first few years of the tree growth (Evans and Probesting, 1985). In California, the fruit yield of navel orange trees on trifoliate rootstock remained the same after the conversion of irrigation method from furrow to drip irrigation (Aljibury et al., 1977). This conversion to drip irrigation resulted in a 25 percent water saving compared to that for the furrow irrigation. In Florida, citrus yield increased following conversion of flood irrigation to trickle irrigation.

Irrigation Scheduling Methods

Irrigation scheduling is the process to determine the amount of water application to a crop grown under specific conditions to replenish the soil water deficit and timing to recommended level for the crop in question. Various techniques have been used for different crops and under different soil types and weather conditions to predict the timing of application and amount of irrigation, as described below.

Soil Water Status Methods

This method is based on monitoring soil water content or soil water tension. The final decision depends on the irrigation criterion, strategy and goal. Irrigators need to define their goal and establish an irrigation criterion and strategy that would be suitable for their condition. There are different methods and devices that can be used to measure soil-water content. These include the feel method, gravitational method, tensiometer, electrical resistance blocks, neutron probe, time domain reflectometer, and capacitance sensors. Most of these methods and devices do not measure soil-water directly; they measure a property of the soil that can be related to soil-water status and are therefore called indirect methods. These methods differ in their ease of use, reliability, cost, and amount of labor required.

Human and Grobler (1990) conducted a field experiment to determine the influence of irrigation scheduling methods and spacing of the plant population on the growth and production of long-season onions on plots equipped with floating lysimeters. Floating lysimeter is a relatively simple and inexpensive lysimeter that was designed to evaluate crop water use under field conditions. This equipment provides an integration of daily evapotranspiration flux with a 0.025 mm sensitivity. The hydrostatic pressure of floatation liquid changes with the weighing variations of the soil-crop vegetation system. Pressure changes are recorded by an electronic piezometer connected with the floatation liquid. The following irrigation scheduling methods were based on crop growth period, soil matrix potential, tensiometers, visual symptoms, class A pan evaporation, and a crop growth mathematical simulation model. The study showed that this irrigation scheduling method had different influence on the leaf area index (LAI) at 15 weeks after transplanting when bulb formation commenced. The irrigation scheduling methods had different effects on the leaf area density (LAD) for the period from transplanting until 15 weeks after until maximum LAI was attained. The LAI at 13 and 15 weeks after transplanting and the LAD for the period of 13 to 17 weeks (maximum LAI) after transplanting correlated significantly with the final dry mass yield of the onions.

Tensiometers were used for irrigation scheduling for mature, large scale, commercial citrus groves in central Florida (Paramasivam et al., 2000b). Irrigation was scheduled when the soil water potential at the 15 and 30 cm depths exceeded either −10 KPa during January to June or −15 KPa July to December to replenish the water deficit (below field capacity) in the top 90 cm of the soil profile. Results of their study showed some excess water drainage was unavoidable in wet summer months (June-September), a period which accounts for over 60 percent of the annual rainfall of approximately 1300 mm. Using multi-sensor capacitance soil water monitoring system, Fares and Alva (2000) were able to optimize irrigation scheduling for young citrus trees grown in sandy soils. A water balance approach was developed, using real-time soil water content data both within and below the rootzone collected using capacitance sensors. Irrigation and rainfall data were used to calculate the daily evapotranspiration and excess water redistribution below the rootzone. Cumulative annual evapotranspiration and drainage below the rootzone were 920 and 890 mm, respectively. This study also demonstrated that most of the drainage occurred during the summer months and the unusually wet fall.

Evapotranspiration Based on Weather Data

Irrigation scheduling based on evapotranspiration calculated using weather data or from pan evaporation data is common for many crops. Hess (1996) used a computer program to simulate the irrigation scheduling for potatoes grown on a medium textured soil. He also tested the effect of four different methods to estimate reference evapotranspiration on the irrigation scheduling. His results showed that irrigation scheduling, i.e., date and amount of application, were largely similar regardless of using long-term mean monthly reference evapotranspiration or the actual daily values. This suggests that reference evapotranspiration is much less variable form year to year than the rainfall. CROPWAT, an irrigation scheduling model developed by FAO, was used to irrigate spring wheat in Bangladesh (Roy, 1998). Irrigation management conditions were varied to estimate the crop production under rainfed and different irrigated regimes. Climatic, soil, and crop data were used as input to the program. The program gives exact time and depth of water to apply for different options and yield reduction along with other outputs. In this experiment each irrigation defined by user, irrigation at critical depletion, below and above critical depletion, fixed interval, fixed depletion and no irrigation timing options were used. Grain yield varied significantly among different treatments in wheat. The highest yield of 3.74 $Mg{\cdot}ha^{-1}$ was obtained when 3 irrigations were given amounting 277 mm water. The model-predicted yield was very close to the observed yield. The result of the study verified the usefulness of computer for irrigation scheduling. Further research can be conducted using the program for irrigation scheduling of other crops.

There are several models that can be used to estimate potential evapotranspiration (Penman, 1963; Jensen and Haise, 1963; Follett et al., 1973; Jensen et al., 1990). New computer models such as SCHED (Buchleiter et al., 1992) and Cropflex (Lorenz and Broner, 2001) can be used to schedule irrigation. NLEAP can also be used to simulate water budgets taking into consideration, rain, irrigation, and potential evapotranspiration and to evaluate the effects of N and irrigation management on NUE and NO_3-N leaching (Beckie et al., 1994; Delgado, et al., 2000; Shaffer and Delgado, 2001).

Nitrogen Management

For comparisons of effectiveness of different crop and fertilizer management, several measures of fertilizer efficiency may be appropriate. The emphasis on developing economically optimum fertilizer rate seems to ignore fate and transport of N and subsequent potential negative effects on the environment. Other estimates of fertilizer efficiency attempt to measure the quantity of fertilizer N recovered by the crop. This method has been used extensively to determine fertilizer N recovery for a variety of crops, soils, and climates. During the recent years, with increased awareness of potential negative effects of NO_3-N leaching and contamination of groundwater, emphasis has been towards developing best management practices (BMPs). These studies considered the fate and transport of N forms in the soil, N recovery by the crop, contribution of plant available N from all sources, and improved management practices to minimize the losses (Alva and Paramasivam 1998, Alva et al., 1998, Paramasivam et al., 2001; 2002; Delgado, 1998; 2001b).

Nitrogen sinks and sources affect yields as well as product quality (Delgado, 2001b). It is important to apply NMP that maximize yields and NUE, as well as crop quality and economic returns to farmers.

These relationship between N levels and crop quality have been observed for crops such as malting barley (*Hordeum vulgare* L.) (Bishop and MacEachern, 1971), tuber quality of potatoes (*Solanum tuberosum* L.) (Westermann et al., 1988; Errebhi et al., 1998) sugarbeets (Roberts et al., 1981), and for fruit crops (Locascio et al., 1984).

Applying higher N rates than needed for maximum economic yield will just increase the residual potential NO_3-N available to leach, increasing the N losses without economic yield benefits (Broadbent and Carlton, 1978; Power and Schepers, 1989). Nitrogen applications should consider realistic yield goals (equal to realistic N sinks), and account for all different N sources (e.g., N budget) (Mortvedt et al., 1996; Ristau 1999; Meisinger, 1984; Ferguson et al., 1991; Westfall et al., 1996; Dahnke and Johnson, 1990; Delgado, 2002a). Site specific characteristics must be considered at the regional and field level while developing BMPs (Ristau, 1999; Delgado, 1999; Doerge et al., 1991; Khosla et al., 2002).

Timing and Sources of Nitrogen

Timing of fertilizer application is another important factor that affects uptake efficiency of applied N. It is basically due to several factors such as crop growth stage, amount and availability of water within the rooting depth of any crop and other macro and micro environmental conditions. For most of the upland crops (annuals and perennials), we have lot of opportunities to apply N and other nutrients (fertilizers) at various times of crop growth stages before, after and at planting time. Even this is true for lowland crops such as rice cultivation. However, under lowland condition, NUE would be substantially reduced due to continuous flooded condition that would result in considerable N losses through denitrification and volatilization.

Applied fertilizer N is used very efficiently when the supply of available N in the soil is closely matched with the demand for N by the crop (Myers, 1987). In addition this efficiency would be decreased substantially if the other environmental conditions were conducive for various forms of losses. Depending on the crops under consideration and other environmental factors, application of N well in advance of seeding or planting of crops would result in low uptake efficiency (Olsen and Swallow, 1984; Bole and Gould, 1986; Bronson et al., 1991; Strong et al., 1992). Synchronizing the fertilizer application with crop demand would result in increased NUE. However, unexpected or various uncontrollable factors such heavy rainfall, extended dry period following the application of fertilizer N would result in increased N losses in the form of leaching, denitrification, or ammonia volatilization (Bacon and Freney, 1989; Freney et al., 1992).

Long-term studies conducted with citrus crop on sandy Entisols of Florida indicated that increasing the frequency of split applications and skipping the fertilizer application during heavy rainfall periods reduced leaching losses of applied N and thereby improve NUE and crop yield (Alva and Paramasivam, 1998; Alva et al., 1998; Paramasivam et al., 2001, 2002). Similarly, these long-term studies further indicated that increasing the number of split applications of liquid fertilizer to 15 improved NUE and crop yield as compared to 4 split applications of water-soluble dry granular fertilizer at the similar annual N rate (Figure 6). Leaching losses of NO_3-N were substantially lower from slow release N fertilizer as compared to that for other two sources (Paramasivam et al., 2001). However, fruit yields were lower with application of slow release form of N as compared to that with either water soluble granular form or fertigation. These results suggest that N release pattern from the slow release fertilizer used in the study failed to meet the crop demand (Alva and Paramasivam, 1998).

Fertigation

For shallow-rooted crops on coarse-textured soils, inadequate irrigation management could increase N leaching losses. Water holding capacity of sandy loam soils is considerably lower than that of the silt loam soils. Thus, irrigation scheduling of coarse textured soils is critical because of greater potential for leaching of water below the rootzone. The leached water also contains soluble nutrients such as NO_3-N, thus, causes leaching of water and N. Citrus production in the arid region is highly dependent on irrigation and adequate N fertilizer input to achieve optimum fruit yield and quality. Thompson et al. (2000) conducted a multi-year young citrus N best management practice experiment to develop appropriate irrigation and N fertilizer management guidelines for young citrus trees. They concluded that excess N rate coupled with reduced frequency of application resulted in greater NO_3-N leaching losses.

Careful management of both N fertilizer and irrigation water is required to minimize NO_3^- leaching below the root zone in irrigated corn (*Zea mays* L.) production. Practices related to management of fertilizer N and irrigation water were evaluated in a series of studies conducted at 79 sites in Nebraska, from 1984 through 1988. Practices evaluated included N credit for NO_3^- in the soil, and in irrigation water, realistic yield goals, and irrigation scheduling according to crop water use. Nitrogen was applied in field length strips at the recommended rate, and at rates 56 $kg \cdot ha^{-1}$ above and below the recommended rate. Groundwater NO_3-N concentrations at sites varied from 0.5 to 46.1 $mg \cdot L^{-1}$. The procedure for determining the recommended fertilizer N rate provided adequate N without reducing yields. Averaged over 79 sites, yield goal was 170 bu/acre; recommended fertilizer N rate was 146 kg $N \cdot ha^{-1}$; yield was 10.9 $Mg \cdot ha^{-1}$; and N applied was decreased by 50 $kg \cdot ha^{-1}$, as N credit in soil and irrigation water. Grain yield often failed to respond to fertilizer N rate because of high NO_3-N concentrations in irrigation water and substantial amounts of NO_3^- in soil (ranging from 17 to 297 $kg \cdot ha^{-1}$ in 120 cm depth soil). With average values for soil and irrigation water N credits, increasing the fertilizer N rate by 112 $kg \cdot ha^{-1}$ increased yield by only 1.3 percent. At the three primary N rates used in these studies (recommended N rate) and 56 $kg \cdot ha^{-1}$ lower or greater rates, irrigation water NO_3-N concentration, irrigation water amount, and soil NO_3^- level all influenced yield more than the variation in fertilizer N rates.

Splitting N applications in small doses at planting, side-dressing and fertigation to coincide with the crop N needs during the growing season can increase yield and NUE (Gunasena and Harris, 1968; Russelle et al., 1981; Stanford and Legg, 1984; Westermann and Kleinkopf, 1985; Oberle and Keeney, 1990; Sowers et al., 1994). Doerge et al. (1991) reported that soil texture should be considered when using fertigation. Accordingly, the frequency of fertigation should be greater for coarse textured soils (5-8) as compared to that for fine textured soils (1-2). Gascho et al. (1984) studied the effect of N-fertigation, N-sidedressing and a combination of both on yield and NUE. The higher yield and NUE were obtained with a combination of N application at planting, side-dress and fertigations (Gascho et al., 1984). These results support the concept that initially during the growing season, when root systems are small, banding N applications in the most active area of the root zone is better. Later in the growing season, when the rooting systems are deeper and the plant canopy is larger, fertigations at small doses in increased frequency of application result in improving uptake efficiency.

Several researchers have found that good N and water management practices can increase yields and reduce NO_3-N leaching in sandy soils under center pivot irrigation (Rehm and Wise, 1975; Watts and Martin, 1981). The concept of using fertigations to increase NUE with center pivot irrigated systems agree with results of other scientists who reported a rapid N uptake by several crops from foliar applications of ^{15}N-urea, ^{15}N-NH_4^+ and ^{15}N-NO_3^- (Garten and Hanson, 1990; Roberts et al., 1991; Bowman and Paul, 1992; Lea-Cox and Syvertsen, 1995). Below et al. (1985) used labeled ^{15}N-urea to study N uptake and transport in corn. They applied 22.3 kg ^{15}N-urea·ha^{-1} seven days pre- and post-anthesis. About 30 percent of the applied ^{15}N-urea was absorbed by the corn at pre- or post-anthesis stage of growth. Below et al. (1985) reported that in two to three weeks after fertigation the absorbed ^{15}N rate of translocation from the leaves to the grain compartment increased. The stalks served as a conduit for this transport of ^{15}N from the leaves to the grain compartment. Foliar applications can also be used to increase uptake from other macro- and micro-nutrients.

Precision Farming and Management Zones

Although it is well known that N dynamics in a system are spatially and temporally variable and that this variability is correlated with yields, the great majority of farmers manage their fields uniformly (King et al., 1999; Khosla and Alley, 1999). Soil types and landscape positions in a field will affect the N dynamics (sinks and sources) and rate of N losses (Delgado et al., 1996; Ortega et al., 1997; Delgado, 2002a). Several researchers have reported that crops respond to this spatial variation as shown by the correlation between crop N status and soil properties (Franzen et al., 1999; King et al., 1999; Delgado and Duke, 2000; Delgado, 2002a). There is potential to use precision farming to manage this variability to improve NUE (Redulla et al., 1996; Delgado, 1999; Khosla et al., 2002). New technologies can be used with grid based sampling systems. This technology however, is time consuming and requires a high cost to determine the N sinks and variable application of N inputs (Khosla and Alley, 1999).

To improve the accounting of this variability while reducing cost, Fleming et al. (1999) proposed the use of management zones that consider N sinks and sources. Soil texture can be important in delineating N management zones for site specific areas to account for differences in residual soil NO_3-N, soil organic matter, yields and NO_3-N leaching losses (Delgado and Duke, 2000; Delgado 2002a). Remote sensing can be used to determine N status to improve NUE for management zones (Scharf et al., 2002). Simulation models can be used to evaluate these different zones and to simulate N budgets and losses (Delgado, 1999; 2002a). Management zones can be dynamic, and as soil properties are improved (e.g., correct acid pH) the productivity may change, requiring changes in the delineation of the management zone (Delgado and Duke, 2000).

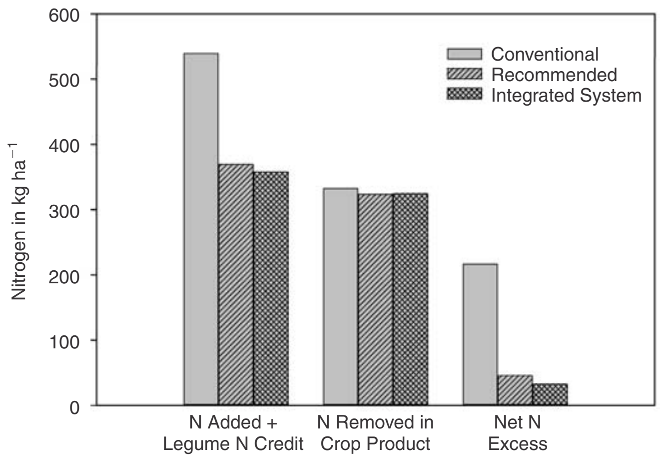
Khosla et al. (2002) reported that physiological NUE was greater when managing zones are based on the site specific soil properties. Agronomic efficiency of N input is greater in high productivity management zones. For example, for optimal agronomic efficiency of N application, N rates could be decreased in the order: 204 kg $N \cdot ha^{-1}$ at the best highest productivity areas, 179 kg $N \cdot ha^{-1}$ at the medium productive areas, and 141 kg $N \cdot ha^{-1}$ at the lowest productive areas.

Benefits from Carbon Management

Nitrate leaching potential is quite high under potato production systems (Chu et al., 1997) because potatoes are grown in sandy loam soils with intensive irrigation. Nitrogen uptake efficiency is quite poor for potatoes, i.e., 33 percent of applied N, as demonstrated in a Minnesota study (Mohamed et al., 1998). Snapp et al. (2001) studied NUE in a potato rotation system in Michigan. They compared three cropping systems: (i) conventional system-maize/rye-winter cover crop/potato rotation. Average N fertilization rate ($kg \cdot ha^{-1}$) of: 210 for maize, 290 for potatoes, and 50 for cover crops; (ii) recommended practice-similar rotation as in (i) but N fertilization rate of 90 $kg \cdot ha^{-1}$ less than that in (i); (iii) integrated practice-maize/winter legume cover crop/potatoes with N rate as in (ii) minus 2 year accumulated legume N credit equivalent to 116 $kg \cdot ha^{-1}$ N. The study showed that most growers applied 50 $kg \cdot ha^{-1}$ N to winter rye crop following potato harvest. The N budget calculated by considering the N input, legume N credit, and N removal from crop products showed a net N excess of 217 $kg \cdot ha^{-1}$ for the conventional practice vs. 46 kg $N \cdot ha^{-1}$ for the recommended N management treatment (Figure 7). This was further decreased to 33 $kg \cdot a^{-1}$ for the integrated system by including a legume cover crop. Since the net excess is an estimate of various N losses including N leaching below the rooting zone, a drastic reduction in net N excess by integrated N management system is likely to contribute to a reduction in N leaching losses.

This study demonstrated that by application of integrated management technology and including cover crops to scavenge excess soil N from main crops, it is possible to minimize the negative impact of agricultural production practices on the environment. This was achieved without sacrificing the yields of main crops. Although the purpose of cover crop is to scavenge the residual soil N (which is about 100

FIGURE 7. Nitrogen added, crop removal and N balance for potato-maize rotation in Michigan (data from Snapp et al., 2001).



kg·ha^{-1}, Vitosh et al., 1997) in the interest of minimizing leaching losses, the growers generally applied N to cover crop as an insurance against possible crop failure. The study also showed despite decreasing N applied by 90 kg·ha^{-1} N in treatment (ii) as compared to that in treatment (i), no significant yield or quality losses were evident during the course of the study. Only 20 percent of Michigan growers surveyed followed the reduced N rate recommendation. About 25 percent of growers surveyed reported that emphasis on environmental quality has curtailed their ability to adequately manage the N use. One-third of the Michigan potato growers did not rely on N monitoring in the plant as a tool for adjusting the fertilizer N application. Washington state potato growers suggested that the university recommendation of N rate for potato (Lang et al., 1999) was not adequate. Thus, they applied one-third more N than what has been recommended by the Cooperative Extension Service as reported in the fertilizer use guidelines (Lang et al., 1999).

Parton et al. (1987) divided the soil organic matter (SOM) into three compartments based on the resident time of the C. Soil organic matter serves as a storage form of N which is released following decomposition and mineralization of N. Soil N dynamics is related to carbon pools and frequently soil organic matter (SOM) is accounted as one of the N sources (Mortvedt et al., 1996; Ristau, 1999). The accountability of N release from SOM can also be done by management zones (Delgado, 1998; 1999; Khosla et al., 2002).

Using winter cover crops (WCC) facilitate scavenging residual soil NO_3-N from the lower depths and recycling it back into the surface soil where crop residue mineralization can release it for the following crop. This N release is also correlated to the C/N ratio of the residue. Generally, application of residues with C/N ratios greater than 35 results in N immobilization. For WCC that have C/N ratios lower than 20 we observe a greater N mineralization potential and greater N fertilizer equivalency available for the next crop (Doran and Smith, 1991). For example, Castellanos et al. (2001) reported that the mineralization of N from broccoli (*Brassica oleracea* L. Italica Group) residue with a C/N ratio lower than 20, cycled 126 kg $N \cdot ha^{-1}$ into the following crop aboveground biomass (corn). In irrigated systems, application of manure is a source of N with up to 58 percent of the total N being transformed into plant available forms during the first year of application (Eghball et al., 2002).

Rotations of leguminous crops can also contribute to an increase in the NUE and reduce NO_3-N leaching losses. Leguminous crop residues have a lower C/N ratio, thus, contributes to a higher N fertilizer equivalence (Doran and Smith, 1991). To take advantage of the higher N fertilizer equivalence of a leguminous crop, this should be rotated with a crop that has a higher NUE (e.g., soybean-corn) (Toth and Fox, 1998; Meek et al., 1995). This kind of rotation increases the N recovery from the crop residue, increase the NUE and reduce NO_3-N leaching (Owens, 1987; Toth and Fox, 1998; Randall et al., 1997). Similar positive effects of greater NUE, through scavenging of residual soil NO_3-N, and mining of NO_3-N from deeper soil layers, have been reported by the use of crop rotations of deeper rooted crops such as small grains with shallower rooted crops (e.g., potato and lettuce) (Delgado, 1998; 2002b). There is potential to develop new varieties with better rooted systems that can contribute to further increase in NUE and to scavenge and mine NO_3-N from lower horizons and underground water resources (Delgado, 2001a). It is important to use crop rotations as a tool to increase NUE of the system (Badaruddin and Meyer, 1994; Kolberg et al., 1999; Delgado, 1998).

The effects of tillage and fertilizer practices on NUE and NO_3-N leaching have been discussed by Meisinger and Delgado (2002). Fall plowing can accelerate the mineralization of organic matter and the release of NO_3-N, increasing the potential for NO_3-N leaching as compared to spring tillage (Cameron and Wild, 1984; Francis, 1995). No till will reduce soil erosion, therefore, decrease the off-site transport of soil and N (Wells, 1984). Cihacewk et al. (1993) reported that 96 percent of the NO_3-N transported with wind erosion sediment can potentially leach out. Increasing crop intensity instead of leaving the system fallow can increase NUE (Westfall et al., 1996). Improved N fertilizer application equipment can improve the accuracy of N applications, which leads to an increase in NUE.

CONCLUSIONS

Nitrogen is a key component of economic viability and sustainability of worldwide agroecosystems. Most agricultural systems have significant spatial and temporal variability that make N management difficult. Since N is such a dynamic and mobile element, management is also affected by irrigation and unpredictable rain events. Nitrogen uptake efficiency for different crop production systems worldwide range from 33 to 55 percent. Thus increasing NUE is a great challenge for nutrient managers who want to maximize yields, and decrease N losses to the environment. There is the need to continue developing new tools and methods to quickly assess N status and to improve N management at regional, field, zone, and site specific levels. Significant advances have been made during the last two decades that are contributing to improve N management and reduce N losses. Further improvements in N management will need to be made within the context of N cycle and N budgets. There are no simple solutions; nutrient managers must consider viable solutions that account for regional and local variability in crops, weather, and soils. There are several universal principles and tools that can be applied to improve N management and increase NUE. New technology is also being developed that will help to increase the accuracy of N needs and N status, and identify hot spots and sensitive areas.

Applying N close to the time of greater demand in multiple applications has demonstrated significant benefits in different geographical regions and for different crops. Crop rotations, especially of shallower and deeper rooted crops, can be used as tool to increase the NUE of shallow rooted systems and to reduce N applications. Rotations that incorporate NO_3-N scavenger crops and legumes are also universal tools that can be used to increase NUE. Another universal concept is the application of irrigation scheduling in phase with crop water needs. It is important to know at each site the soil water holding capacities, the evapotranspiration rate and precipitation. Evapotranspiration models and expert systems could be used to improve irrigation scheduling, and may need to be calibrated in different production systems based on soil water holding capacity. This chapter emphasizes the need to follow a holistic approach that considers water and N management for a given cropping system and soil condition. We need to follow best water management practices (BMP) that facilitate retention of N in the soil profile, within the rooting zone. Rotation of a deep rooted crop following a shallow rooted crop provides benefit of scavenging N from the deeper soil layers. Rotations have additional benefits such as reduction of disease and weed problems that will increase yields thus leading to greater NUE. Use of simulation models to assess sensitive areas of the fields is also a BMP option. New technologies will facilitate the application of these universal principles at a site specific level. The use of remote sensing, and development of management zones will contribute to increase NUE for precise conservation of water quality, reducing N losses from sensitive areas of the field. The calibration, use and development of quick techniques to determine N status will also contribute to increase NUE. Although there is the need to continue developing BMP to improve NUE, maximize yields, product quality and economic returns to farmers, there are universal principles and new technology that can contribute to improve NUE of irrigated system, while reducing the N losses to the environment.

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