Principles for managing nitrogen leaching

J.J. Meisinger and J.A. Delgado

ABSTRACT: Managing leaching presents a challenge to nutrient managers who must develop nitrogen (N) management plans that consider rate and application strategies that account for soil properties, hydrology, and crop-tillage systems of specific sites. Nitrogen-leaching losses from common grain-production systems typically range from 10% to 30% of the total N input. Major leaching events occur when soil N concentrations are high and water is moving through the soil profile. The universal tools for managing N leaching include understanding the soil-crop-hydrologic cycle, avoiding excess N applications, and applying N in phase with crop demand. Specific cropping system tools for managing leaching include use of grass cover crops, adding a legume to a rotation, and adding crops that more fully utilize the soil-water resources. The primary water-management tool to reduce N leaching is irrigation scheduling. Other watershed approaches to reduce leaching losses include use of riparian zones and conservation reserve program areas. Site monitoring tools such as the pre-sidedress soil-nitrate test, the leaf chlorophyll meter, and tissue-nitrate tests are useful in identifying N-sufficient sites and avoiding excess N rates. Real-time monitoring techniques, such as the N Reflectance Index, can be combined with global positioning systems and geographic information systems to produce maps of the crop N status. Crop simulation models can also be used to integrate N and water dynamics during a growing season, and they can provide guidance in designing practices for reducing N leaching. The application of the above N management tools to fields, or to specific management areas within fields, will improve crop N recoveries with subsequent reductions in N leaching.

Keywords: Irrigation, nitrate, nitrogen leaching, nutrient leaching, nutrient management plan

Controlling nitrogen (N) leaching presents a major challenge for nutrient managers. Nutrient management strategies regarding rate and time of N applications must be developed for the specific soils, hydrology, and crop-tillage systems of individual fields. However, leaching is only one of several outputs from the soil N cycle. The other major outputs are crop uptake, denitrification, and ammonia volatilization (Legg and Meisinger 1982, Tisdale and Nelson 1975, Stevenson 1982). Nitrate nitrogen (NO₃-N) is a water-soluble and mobile form of N that is highly susceptible to leaching. However, if the soil is saturated and anaerobic conditions develop, NO₃-N can be converted to N₂ and N₂O gases by denitrification. Ammonia losses can also occur from surface-applied manure, urea, or N sources that form low-solubility reaction products in calcareous soils. This discussion will focus on N leaching, but one must also keep in mind the other N-loss processes to design an efficient N management system for a given site.

Nutrient leaching is usually applied to NO₃-N movement out of the root zone, but it can also occur for phosphorus. Sims et al. (1998) and Sharpley et al. (1998) have reviewed the principles and factors influencing phosphorus leaching and have summarized strategies for managing these losses. This paper will focus on the principles and practices for managing N leaching from across the United States, including both dryland and irrigated systems. Dinnes et al. (2002) have summarized N management strategies to reduce NO₃-N leaching in Midwest tile-drained systems. Nitrate leaching losses can vary from 0% to 60% of the applied N, but losses from common grain-production systems would range from 10% to 30% of N.

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Nitrogen leaching requires water movement and N present in the soil solution. The quantitative expression for N leaching includes only two factors, the volume of leachate and the NO$_3$-N concentration. The mathematical expression is:

$$\text{Leaching loss} = (\text{leachate volume}) \times (\text{N concentration of leachate}).$$  \hspace{1cm} (1)

Equation 1 shows there are two fundamental approaches to manage leaching. One approach is to manage the leachate volume; the other is to control the soil NO$_3$-N concentration. The goals of this paper are: 1) to describe the general principles for managing N leaching, 2) to consider several specific practices for cropping systems and water management, and 3) to discuss new technologies and opportunities for managing N leaching.

**Universal Tools for Managing Nitrogen Leaching**

Significant leaching occurs when: 1) soil N concentrations are high, and 2) water is moving through the soil profile. The universally applicable tools for managing N leaching include: obtaining a working knowledge of the soil-crop-hydrologic cycle, avoiding excess N additions, and applying N in phase with crop demand. The majority of the management strategies for controlling leaching at a given site will involve the application of one or more of these universal tools for the site-specific conditions of the local farm.

**Know the soil-crop-hydrologic cycle.** Knowledge of the soil-crop-hydrologic cycle is fundamental for identifying the times of the year and hydrologic events that promote leaching, that is, the times when the soil is near field capacity and water inputs through precipitation and/or irrigation exceed crop water loss by evapotranspiration (ET). Information on the soil-crop-hydrologic cycle for an area of the country can be obtained by performing simulations with N models, such as NLEAP (see examples below), or by consultation with local Extension or Natural Resources Conservation Service (NRCS) personnel.

A typical humid-region monthly water balance is given in Figure 1 for a Norfolk sandy loam growing corn (Zea mays L.) in the Piedmont region of North Carolina (Smith and Cassel 1991). The monthly water input through rainfall (triangle symbols) is about uniform over the year, while corn water use by ET (solid line) is greatest in the summer months. The surplus water, the difference between precipitation and ET, is used to recharge the soil moisture in the fall and is the driving force for leaching (solid circles) during the winter and early-spring seasons when the soil profile is full of water. Thus, the average soil-hydrologic cycle for this location shows a long leaching season that occurs during the late-fall, winter, and early-spring. This pattern of high nongrowing season leaching losses in humid climates is well-supported by the experimental data of Toth and Fox (1998), Owens (1987), and Durieux et al. (1995). Without a winter crop, there is little a farmer can do to avoid this winter-to-spring "leaching season," so leaching management strategies in this situation should focus on reducing the soil N concentration in the fall before the start of the leaching season. Specific strategies for reducing the fall N concentration are discussed below. Of course, the specific soil-hydrologic cycle for a given year and field will vary from the general case of Figure 1 because of year-to-year differences in rainfall and differences in soil waterholding capacities and water infiltration rates over the field. These within-field differences can be managed through the use of management models, such as NLEAP (discussed below), and the use of spatial databases that can capture within-field variability for site-specific management (discussed below).

A typical soil-crop-hydrologic cycle for an arid region is given in Figure 2 for a loamy sand in south-central Colorado growing irrigated spring barley (Hordeum vulgare L.). The water inputs (triangle symbols) come from rainfall, which averages 15 mm (0.6 in) per month, and from irrigation that is only applied during the growing season. The spring barley ET (solid line) is highest during the spring and early-summer months and is low during the fall and winter. Irrigation management practices and the occurrence of large rain events greater than 38 mm (1.5 in) determine the leaching risks in this climate for irrigated small grains. The quantity of soil water at the time of the water input and the soil infiltration characteristics determine the extent of leaching from these periodic rainfalls or irrigations. If the soil is at field capacity, then conditions are right for water movement and potential leaching. One such 38 mm (1.5 in) rain event is depicted in Figure 2 in early May, an event that occurred shortly after irrigation and generated about 33 mm (1.3 in) of percolation (solid circles) below the root zone. Managing N leaching in...
this arid climate should use practices that focus on both irrigation management and management of the soil N concentrations. Nitrate leaching below the root zone can also occur in the dryland agriculture of the Great Plains, especially for traditional cropping systems (e.g., wheat (*Triticum aestivum* L.)-fallow systems) using modern, no-till, water-conservation strategies (Westfall et al. 1996). However, nitrate leaching in dryland agriculture usually occurs over several decades and is considered to have minimal environmental impact on the deep aquifers common in the region (Evans et al. 1994, Westfall et al. 1996).

Figures 1 and 2 illustrate that knowledge of the soil-crop-hydrologic cycle is fundamental for understanding the dynamics of N leaching. This knowledge should form the foundation for designing management strategies for controlling leaching. The soil-crop-hydrologic diagrams will vary with different soils, cropping systems, and rainfall/irrigation practices. Soil properties will also affect the soil-crop-hydrologic cycle and include: soil texture (low water-holding, coarse-textured soils promote leaching), infiltration rate (high infiltration rates increase leaching), and rooting depth (root restrictions encourage leaching). The main crop factors influencing the soil-crop-hydrologic cycle are: length of the growing season (short growing-season crops are prone to leaching), time of year when crop growth rate is high (high N uptake reduces leaching), and rooting depth (deep-rooted crops reduce leaching). Consequently, these diagrams can be used to develop site-specific management strategies for areas within fields or for various cropping systems.

**Apply proper rate of nitrogen.** The second universal principle for managing leaching is to apply the proper amount of N for the expected crop—i.e., avoid excess N additions. Nitrogen added in excess of crop need usually remains in the soil at the end of the cropping season and is vulnerable to leaching. Broadbent and Carlton (1978) conducted several irrigated N-rate studies with corn in California, where they observed minimal increases in soil residual N (compared with the control) up to the point of maximum economic yield (about 200 kg N ha⁻¹ or 175 lb N ac⁻¹). However, additional N inputs up to 335 kg N ha⁻¹ (300 lb N ac⁻¹) caused soil residual inorganic N to increase from about 100 kg N ha⁻¹ (90 lb N ac⁻¹) at the maximum economic yield rate to 225 kg N ha⁻¹ (200 lb N ac⁻¹) in the 2.4 m (8 ft) depth of soil sampled at the end of the season. Similarly, Power and Schepers (1989) concluded that applying the correct amount of N fertilizer was the most important single factor for reducing N leaching. Thus, the key to avoiding large levels of residual NO₃-N is to avoid over-fertilization—i.e., apply the recommended rate of N for the expected crop. Estimating optimal N additions for cropping systems has been an important area of applied research for soil and crop scientists during the last 50 years.

The Cooperative Extension Service in each state has implemented N-rate recommendations specific to each state’s soil-crop-tillage systems. It is beyond the scope of this paper to describe these programs in detail, but Table 1 lists several key elements that are common to most recommendation systems, using corn as an example crop. In general, one should add fertilizer N for a realistic yield goal after making allowances: for residual soil NO₃-N (especially in sub-humid regions), for manure additions, for a previous legume crop, and for N contained in irrigation water (Meisinger 1984, Ferguson et al. 1991, Westfall et al. 1996, Dahnke and Johnson 1990).

**Apply nitrogen in phase with crop demand.** The third universal principle for managing N leaching is to apply the N at a time and in a soil location that allows rapid crop utilization—i.e., apply N in harmony with crop need. Crop development involves an establishment period when crop N need is low, a vegetative development period with rapid leaf growth and high N need, a period of reproductive development when dry matter production and N demand is high, and a period of senescence when the reproductive organs reach maturity and N uptake is low. Cumulative N need usually follows an S-shaped curve, with slow accumulations during establishment and an exponential

![Figure 2](https://example.com/figure2.png)

**Figure 2**

Soil-crop-hydrologic cycle for an irrigated loamy sand growing spring barley in Colorado showing precipitation plus irrigation (Ppt + Irr, triangles), barley evapotranspiration (ET, solid line), soil water content to 0.3 m (Soil W, diamonds), and drainage below 0.9 m (Drain, circles) data adapted from Delgado et al. (2003a).

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**Table 1. Common factors considered in nutrient recommendation programs.**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Some typical approaches for including factor in recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected yield</td>
<td>Average yield over 5 years omitting drought years; average yield plus 10%</td>
</tr>
<tr>
<td>Legume credit</td>
<td>Alfalfa credited with 50-100 kg N ha⁻¹; soybean credit 30-50 kg N ha⁻¹</td>
</tr>
<tr>
<td>Manure credit</td>
<td>Manure total N and NH₄-N analysis, plus manure application method</td>
</tr>
<tr>
<td>Profile nitrate</td>
<td>Direct analysis of 90 cm soil sample for NO₃-N</td>
</tr>
<tr>
<td>Irrigation N</td>
<td>Direct analysis of irrigation water</td>
</tr>
<tr>
<td>Other factors</td>
<td>Soil pre-sidedress NO₃-N analysis; adjust for time of application (pre-plant vs. sidedress); adjust for additives (e.g., nitrification inhibitor)</td>
</tr>
</tbody>
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*Some typical approaches for including factor in recommendation*
uptake rate during the vegetative and reproductive phases. Applying N in phase with crop demand provides high soil-N concentrations at the times needed for growth, while minimizing the exposure time of the high N concentrations to leaching losses (Power et al. 1998). Smith and Casel (1991) have estimated the probable leaching depth for various N application times for the soil-crop-hydrologic cycle depicted in Figure 1. Their results show that a November N application would probably leach to 1.5 m (60 in) by April 1, while a May 1 application would remain in the surface 30 cm (12 in) of soil. Data from southern Minnesota (Randall et al. 1992, Randall and Mulla 2002) have shown that spring applications increase nitrogen use efficiency (NUE) by more than 20% compared with fall-applied N. Iowa data (Sanchez and Blackmer 1988) have reported that 50% to 64% of fall-applied N was lost from the upper 1.5 m (5 ft) of soil by processes other than plant uptake. Proper timing is especially important for crops growing during the heart of the growing season (e.g., winter wheat grown in humid climates), for shallow-rooted crops with short growing seasons (e.g., vegetable crops harvested for fresh market), and for crops grown on soils with restricted rooting depths (e.g., crops grown on soils with hard-pans or subsoil acidity). Proper placement of N is also important; lowest N losses are obtained if N is placed in the zone of active water uptake. Some examples of techniques that encourage proper timing and placement include: split N applications, N applications to forage grasses after each harvest, and application of N with high-clearance equipment or through irrigation systems during the period of rapid crop growth.

**Add a legume to a cereal-grain system.**

Adding a legume, such as soybeans ( Glycine max Merr.), to a cereal-grain system is one way to reduce the risks of N leaching. A six-year study monitoring tile-drain effluent in Minnesota (Randall et al. 1997a) reported flow-weighted NO3-N concentrations of 32 mg NO3-N L-1 (32 ppm) for continuous corn (C-C) and 24 mg NO3-N L-1 (24 ppm) for a corn-soybean (C-Sb) rotation. The C-Sb rotation also resulted in a 17% increase in drainage volume compared with C-C. The average total N losses (NO3-N concentration x tile flow) for these rotations were 36 kg N ha-1 yr-1 (32 lb N ac-1 yr-1) for C-C and 34 kg N ha-1 yr-1 (30 lb N ac-1 yr-1) for C-Sb. Similar tile-drainage studies in Iowa (Kanwar et al. 1997) have reported three-year average nitrate concentrations of 30 mg NO3-N L-1 (30 ppm) for C-C, compared with 14 mg NO3-N L-1 (14 ppm) for C-Sb. Corresponding total NO3-N losses in the drainage were 58 kg N ha-1 yr-1 (52 lb N ac-1 yr-1) for C-C, compared with 29 kg N ha-1 yr-1 (26 lb N ac-1 yr-1) for C-Sb. Other studies in Ohio with large monolith lysimeters (Owens et al. 1995, Owens et al. 2000) reported lowest leaching losses during the Sb phase of a C-Sb rotation and concluded that a C-Sb rotation was one strategy for reducing N losses to groundwater, particularly if a soybean fertilizer-N credit was applied to the succeeding corn crop. The benefits of the C-Sb rotation are usually ascribed to lower fertilizer N inputs for the rotated system and more vigorous corn growth caused by a reduction of disease and insects. However, the leachate NO3-N concentrations during the Sb phase of the Ohio study were only reduced about 5 mg N L-1 (5 ppm) compared with the corn phase, which still produced a significant N leaching loss during the soybean years. Thus, a continuous grain-crop rotation, such as a C-Sb rotation, can moderate nitrate-leaching losses compared with C-C. However, the largest crop rotation benefit will come from adding a forage crop to the system. (See following discussion.)

Adding a forage legume, such as alfalfa (Medicago sativa L.), to a rotation is also a very effective approach to reducing leaching. The benefits of adding alfalfa arise from alfalfa’s deep-root system, long growing season, high water use, and reliance on biological N fixation that supplies N in phase with crop growth. Toth and Fox (1998) conducted a four-year study using zero-tension pan lysimeters in Pennsylvania, reporting N concentrations of 4 mg NO3-N L-1 (4 ppm) below alfalfa compared with 15 mg NO3-N L-1 (15 ppm) leached from C-C receiving the economic-optimum rate of fertilizer N. Randall et al. (1997a) summarized a six-year Minnesota study that found average tile-drain effluent from C-C to be 32 mg NO3-N L-1 (32 ppm), while alfalfa drain effluent averaged 3 mg NO3-N L-1 (3 ppm); corresponding total N losses were 36 kg N ha-1 yr-1 (32 lb N ac-1 yr-1) for C-C and 1 kg N ha-1 yr-1 (1 lb N ac-1 yr-1) for alfalfa. Owens (1987) also reported that NO3-N concentrations from large monolith lysimeters were lower under alfalfa than under corn—e.g., leachate during two years of alfalfa was about 20 mg NO3-N L-1 (20 ppm) lower than leachate from two years of corn fertilized with 156 kg N ha-1 (140 lb N ac-1). Soil nitrate concentrations below alfalfa crops have been consistently shown to be much lower than under corn, which leads to concurrent reductions in NO3-N leaching over the span of the rotation cycle.

The benefit of rotating a legume into a cereal-grain system must also include proper accounting for the increased N available to the crop after the alfalfa. For example, Toth and Fox (1998) reported average leachate NO3-N concentrations of 15 mg N L-1 (15 ppm) for unfertilized corn after alfalfa (the recommended N practice in Pennsylvania), compared with concentrations of 18 or 24 mg NO3-N L-1 (18 to 24 ppm) for post-alfalfa corn receiving 50 or 100 kg N ha-1 (45 or 90 lb N ac-1), respectively. Obviously, adjusting the N fertilizer rate for a previous legume is an important practice to fully benefit from adding a legume into a cropping system. Leaching after an alfalfa crop can also be managed by using high-N demand crops (e.g., corn or wheat) rather than low-N demand legumes (e.g., field beans (Phaseolus vulgaris L.), Meck et al. (1995) estimated that leaching below 1.35 m (4.5 ft) from two years of beans after alfalfa was 121 kg N ha-1 (108 lb N ac-1), while comparable leaching losses with two years of cereals (corn-wheat sequence) was 67 kg N ha-1 (60 lb N ac-1).

**Expand the use of soil resources.** A cropping system’s use of soil resources can be improved by growing species with different rooting depths, growing a more crop-intense rotation, or growing varieties with greater tolerances to growth-limiting factors such as subsoil acidity, salinity, or water stress. Delgado
Both of these reviews concluded that cover crops have been reviewed by Meisinger et al. (1991) and summarized by Dabney et al. (2001). A major factor affecting leaching was the species of cover crop. The average percent reduction in NO$_3$-N leaching was 70% for non-legume covers and 23% for legume covers.

Cover crop research in Maryland (Shipley et al. 1992) assessed the ability of five cover crops to conserve $^{15}$N labeled fertilizer applied to the previous corn crop by measuring the recovery of the $^{15}$N by the winter cover crop. The study reported that a rye (Secale cereale L.) cover crop recovered 60% of the corn fertilizer N at mid-April, the usual kill date for covers in Maryland. The corresponding recovery of $^{15}$N by annual ryegrass (Lolium multiflorum Lam.) was 40%, while covers of hairy vetch (Vicia villosa Roth), crimson clover (Trifolium incarnatum L.) or native weeds recovered less than 10% of the corn fertilizer. The greater effectiveness of the grass cover crops is attributed to a faster and deeper colonization of the root zone in the fall, greater cool-season growth, and greater winter hardiness.

Delgado et al. (1999) conducted studies with winter cover crops (rye, Secale cereale L., and wheat) in Colorado and found that when used as scavenger crops in lettuce (Lactuca sativa L.) potato, and spinach (Spinacia oleracea L.) rotations, they reduce wind erosion, scavenge from 20 to 300 kg N ha$^{-1}$ (18 to 268 lb N ac$^{-1}$) and can serve as forages. The amount of N scavenged will depend on the initial residual soil NO$_3$-N and time of planting. The C/N ratio in the winter cover crops can be kept lower than 20 by killing or by incorporating them early in spring, which increases the potential for mineralization and N cycling during the next growing season.

Meisinger et al. (1991) used the EPIC model to estimate the impact of winter covers on nitrate leaching across the United States. They concluded that the greatest potentials for cover crops were in humid regions, particularly the Mid-Atlantic and Southeast, and in irrigated agriculture. Delgado (1998, 1999, 2001a) conducted NLEAP simulations of winter cover crops and found that they reduced NO$_3$-N leaching and increased the NUE of the system when included in lettuce and potato rotations.

Managing adjacent ecosystems, tillage, equipment, nitrification inhibitors, other approaches. Additional approaches for managing leaching include the use of nonagromonic land within a watershed, such as Conservation Reserve Program (CRP) areas and riparian zones, and use of tillage practices and improved N application equipment to reduce N leaching. Nitrogen fertilizer additives, such as nitrification inhibitors, also offer opportunities to reduce N leaching.

The CRP acres have been shown to markedly reduce nitrate leaching. Randall et al. (1997a) reported six-year average NO$_3$-N concentrations from tile drainage beneath CRP plots, C-C plots, and C-Sb plots of 2, 32, and 24 mg NO$_3$-N L$^{-1}$ (2, 32, and 24 ppm), respectively. The unfertilized CRP system exerted this marked reduction in leaching by providing a deep-rooted perennial grass that actively immobilized N during the entire growing season. A modest CRP area within a watershed could therefore dilute the recharge from grain-producing areas and thereby reduce N leaching from the watershed.

Riparian zones, areas of native trees or shrubs adjacent to streams, have been shown to be effective N sinks for NO$_3$-N that leaches out of agricultural areas en route to surface waters. Riparian zones will have the largest impact in humid regions and in areas where groundwater flow from agricultural areas is forced through the root zone of the riparian area before it enters adjacent surface waters. For example, Jacobs and Gilliam (1985) showed that average annual NO$_3$-N concentration leaching from an agricultural area in North Carolina’s Coastal Plain was 15 mg NO$_3$-N L$^{-1}$ (15 ppm), but the average concentration of water emerging from the adjacent riparian zone was 1–12 mg NO$_3$-N L$^{-1}$ (1–2 ppm). The corresponding quantities of N leached were 31 kg N ha$^{-1}$ (28 lb N ac$^{-1}$) from the agricultural area, compared with 5 kg N ha$^{-1}$ (4 lb N ac$^{-1}$) lost from the riparian area. Other riparian research by Lowrance et al. (1984) in Georgia and by Peterjohn and Correll (1984) in Maryland have reported that riparian zones can reduce NO$_3$-N losses from agricultural areas by 50% to 90%. Most researchers agree that the primary mechanisms of nitrate removal by riparian areas are plant uptake and denitrification, although the precise mechanism will vary with the location depending on climate, extent of vegetative growth, and degree of water saturation. Dines et al. (2002) present an extended discussion on riparian zones and wetlands.

Tillage practices, per se, usually have only secondary effects on nitrate leaching; but the timing of the tillage can impact the timing of nitrate release from decomposition of soil organic matter and residues. Cameron and...
Wild (1984) reported significant NO$_3$-N leaching from fall plowing of temporary grassland in England. New Zealand research by Francis (1995) reported that leaching losses from early-fall tillage of temporary legume pastures amounted to 72-106 kg N ha$^{-1}$ (65-95 lb N ac$^{-1}$), losses from late-fall tillage were 8 to 52 kg N ha$^{-1}$ (7 to 45 lb N ac$^{-1}$), while losses from spring tillage were 2 to 15 kg N ha$^{-1}$ (2 to 13 lb N ac$^{-1}$). Kanwar et al. (1997) compared leaching losses of tile drains from moldboard plowing, chisel plowing, ridge tillage, and no-tillage and reported that total N losses were not affected by the tillage treatments. Randall and Iragavarapu (1995) summarized an 11-year C-C study comparing no-tillage (NT) with moldboard plow tillage (PT) on a poorly drained, south-eastern Minnesota soil fertilized with 200 kg N ha$^{-1}$ (175 lb N ac$^{-1}$) annually. They reported 12% higher tile-drainage with NT (315 mm with NT vs. 280 mm with PT), but a 5% reduction in average N leaching with NT because of lower NO$_3$-N concentrations with NT. Randall and Iragavarapu (1995) concluded that PT had a positive effect on grain yield and grain N removal compared with NT, but tillage had minimal impact on NO$_3$-N losses to tile drainage.

Improved N application equipment can also reduce N leaching by improving the accuracy of N application rates and increasing crop NUE. Researchers have found that improving the conventional anhydrous ammonia distribution manifold can markedly improve the accuracy of N application rates (Boyd et al. 2000, Hanna et al. 1999). Conventional manifolds commonly have coefficients of variation among application knives of 10% to 70%, depending on N rate and operating conditions. Improved manifolds, such as the vertical-dam manifolds, can markedly reduce this variability (Boyd et al. 2000, Hanna et al. 1999). Other application equipment is aimed at improving the placement of liquid urea-ammonium-nitrate (UAN) fertilizers. The point-injector system was designed to inject liquid N through projecting spokes on a wheel, which places the N below the soil surface with minimal disturbance of surface residues (Baker et al. 1989). Randall et al. (1997) summarized a three-year study that found that pre-emergent point injection of UAN into the ridge of ridge-tillage corn optimized N uptake, grain yield, and economic return compared with band or broadcast applications of UAN.

Another approach knifes N into the soil and then covers the knife zone with a localized compacted dome (LCD) of soil to reduce water infiltration and leaching through the knife zone (Ressler et al. 1997). A nonweighing drainage lysimeter evaluation of the LCD equipment was conducted in Iowa (Ressler et al. 1998) that followed the movement of an anion tracer from LCD and conventional application techniques. The study reported that at the end of 18 months, 25% of the tracer applied by a conventional knife shank leached into the subsurface drains, while only 13% leached from the LCD application method. The above improvements in application equipment offer the potential of increasing NUE, but the general applicability of these techniques will require further testing under a wider range of soils and climates.

Nitrification inhibitors (NI) delay the conversion of ammonium-N to nitrate-N. They offer the potential of reducing leaching by extending the time that fertilizer ammonium-N can be retained on soil cation exchange sites, rather than being converted to mobile NO$_3$-N. The effect of NI on nitrate leaching has been studied in Minnesota and Ohio. A six-year study in Ohio grew corn on undisturbed-soil monolith lysimeters (Owens 1987) and reported nitrate leaching of 48% of the applied N for untreated urea, while NI-treated urea lost 35% of the 336 kg N ha$^{-1}$ (300 lb N ac$^{-1}$) that was applied. The Ohio study intentionally used an excess rate of fertilizer N to more easily measure the leaching effects. Owens (1987) concluded that NIs have the potential to reduce NO$_3$-N leaching for ammonium fertilizers. Nitrification inhibitors were also evaluated by Timmons (1984), using field lysimeters on a sandy loam soil fertilized with 224 kg urea-N ha$^{-1}$ (200 lb N ac$^{-1}$). Timmons (1984) reported that NI reduced annual NO$_3$-N leaching losses by about 7% compared with nontreated urea over the three-year study, the greatest benefits occurring during the growing season. Timmons (1984) also concluded that although NI can help reduce growing-season NO$_3$-N leaching on irrigated sandy soils, the N not used by the crop would still be subject to over-winter leaching. Thus, it is important to adjust fertilizer N rates for other N management practices (such as CRF) that can reduce leaching and increase crop N utilization. Corn N response experiments with NI in Ohio (Stehouwer and Johnson 1990) and Minnesota (Randall et al. 1992) have reported small yield increases from NI used with fall-applied N, but little or no yield benefit from NI used with spring-applied N. Fall N applications, with or without a NI, were associated with lower yields and lower crop N contents than spring-applied N. Walters and Malzer (1990) also grew irrigated corn on a sandy-loam soil in Minnesota and monitored nitrate leaching with field lysimeters that received two rates of urea-N (90 or 180 kg N ha$^{-1}$), two NI treatments (with or without NI), and two fertilizer incorporation treatments (incorporated or not incorporated).

The results of their three-year study showed that the NI influenced the time of nitrate leaching (leaching losses were delayed 25 to 50 days by using the NI), but the total quantity of N lost through leaching was not affected by the NI. The largest factor affecting NO$_3$-N leaching was the rate of fertilizer N, leaching losses amounting to 18% of the 90 kg N ha$^{-1}$ (80 lb N ac$^{-1}$) addition but increasing to 30% of the 180 kg N ha$^{-1}$ (160 lb N ac$^{-1}$) addition. The authors concluded that NI may delay nitrate leaching, but NI will be most effective if combined with other N-leaching management practices, such as proper N rates, soil nitrate testing, and conservative irrigation-water management.

Shoji et al. (2001) discussed the potential to use controlled release fertilizers (CRF) and NI with urea-based fertilizers to increase NUE and to conserve air quality. They reported that CRF at 50% of the N rates used by traditional farmers were able to produce the same total potato tuber yields as the traditional practices. If the rate of N release from CRF can be set to match the crop demand, there is a significant potential to reduce N losses. Shoji et al. (2001) estimated that the maximum possible reduction in environmental impact from N fertilizer management was 67%, which resulted from reductions in leaching and atmospheric losses.

**Water Management Tools for Reducing Leaching**

Nitrogen leaching is driven by water transport (Equation 1), which interacts with the N management practices and the natural hydrology of a given site. Water-management tools are the most direct methods of limiting N leaching. The most common tools are irrigation management and water-table control strategies.

**Irrigation scheduling.** About 17% of U.S. cropland is irrigated, with about 75% of this...
acreage lying west of the Mississippi River (USDA-NRCS 2000). The water resources used in irrigation are derived from groundwater (60%), rivers (22%), local ponds (10%), or a combination of these sources. Yields on irrigated land are frequently double of those on rain-fed systems (Rangel 1987, Eek et al. 1990, Tribe 1994). Irrigated lands usually include cropping systems and soils that are vulnerable to leaching, i.e., coarse-textured soils, shallow-rooted vegetable crops, and high fertilizer rates.

In irrigated systems, excess irrigation or poorly timed irrigation is a primary factor contributing to N leaching. Irrigation scheduling is an important tool for applying the proper amount of water at the proper time. Irrigation scheduling systematically integrates local factors such as crop growth and water use, soil infiltration, soil water content, soil texture, water application systems, and rainfall into a water-management system that forecasts irrigation needs for a specific field. To ensure that water in not moving past the root zone, irrigation scheduling systems typically monitor: local weather conditions that affect ET, soil water content before and after irrigation, and irrigation system flow rate, pressure, timing device, and application uniformity. Soil water content before and after irrigation can be monitored with hand probes, tensiometers, resistance blocks, and time domain reflectance (TDR) instruments. Soil-water monitoring is important for controlling water movement, which is fundamental for reducing leaching. Several authors such as Penman (1963), Jensen and Haise (1963) or the modified Jensen-Haise method (Follett et al. 1973, Jensen et al. 1990) have developed equations to estimate reference ET, which undergirds irrigation scheduling. Computer models such as SCHED (Buchleiter et al. 1992) and CropFlex (Lorenz and Broner 2001) can be used to schedule irrigation for specific fields.

With surface irrigation, run distances and stream-size controls can optimize efficiency, with the goal of reducing erosion and N transport. Additionally, polyacrilamide (PAM) can reduce soil erosion and off-site transport of N. Irrigation tail water should be recovered in ponds or reused if possible. Higher-efficiency surface systems, such as surge flows, sprinkler, and/or drip irrigation systems should also be considered to upgrade less-efficient systems.

Irrigation research by Herget (1986) on sandy soils in Nebraska documented growing-season leaching for two sprinkler irrigation rates of 0.85 ET and 1.0 ET. The study reported average growing-season drainage of 85 mm (3.3 in) for the 0.85 ET treatment, which transported 61 kg N ha⁻¹ (54 lb N ac⁻¹), while the 1.0 ET treatment lost an average of 187 mm (7.5 in) of leachate transporting 111 kg N ha⁻¹ (99 lb N ac⁻¹). A five-year research project in Minnesota (Timmons and Dylla 1981) used field lysimeters on a sandy loam soil and also reported lower percolate volumes for deficit-irrigation treatments—e.g., percolate losses averaged 112 mm vs. 180 mm (4.6 in vs. 7.2 in) for irrigation scheduled to add 50% of water use or 100% of water use, respectively. The corresponding NO₃-N leaching losses averaged 81 kg N ha⁻¹ (72 lb N ac⁻¹) for the deficit-irrigation treatment and 106 kg N ha⁻¹ (95 lb N ac⁻¹) for the full-irrigation treatment. These studies concluded that irrigation scheduling of modest water inputs (less than 1.0 ET) were especially important on sands. However, water management must also be combined with prudent N management (proper rate and time of N application) to minimize NO₃-N leaching. The N simulation model NLEAP can also be used to simulate water budgets and irrigation scheduling, along with N dynamics and nitrate leaching (Beckie et al. 1994, Delgado et al. 2000b, Shaffer and Delgado 2001).

The effects of irrigation scheduling, combined with N management, were evaluated at 79 corn production fields in Nebraska by Fergusson et al. (1991), who studied both center-pivot and furrow-irrigation systems. Nitrogen management practices used fertilizer N recommendations based on yield goal (average yield for previous five years plus 5%), pre-plant soil nitrate N content to 1.2 m (4 ft), and nitrate content of irrigation water. This study reported that with careful water management and proper N accounting, an average grain yield of 10.8 Mg ha⁻¹ (173 bu ac⁻¹) was achieved with 145 kg fertilizer-N ha⁻¹ (130 lbs N ac⁻¹); the remaining N was supplied from 85 kg N ha⁻¹ of soil nitrate (76 lbs N ac⁻¹) and 21 kg N ha⁻¹ in irrigation water (19 lbs N ac⁻¹). The authors found that yield was surprisingly insensitive to fertilizer N rate. Instead, yield was influenced more by irrigation water NO₃-N concentration, amount of irrigation, and soil NO₃-N level.

Delgado (2001a) reported results from studies conducted on 38 fields located on several farms in south-central Colorado where the recommended management practices (Ristau 1999) were implemented. Nitrogen and water budgets were studied for these sites, including N fertilizer applications, NO₃-N background in irrigation water, and initial and final residual inorganic NO₃-N and NH₄-N. Nitrogen cycling and mineralization from crop residues and soil organic matter were simulated with the NLEAP model. These water and N budget studies found that, even with best management practices for shallow rooted crops, there was a net minimum movement of NO₃-N out of the soil profile (0 to 0.9 m) (0 to 36 in) that ranged from 5 to 12 kg NO₃-N ha⁻¹ (5 to 11 lb N ac⁻¹). For deeper-rooted crops, such as small grains, there was a net recovery of NO₃-N from underground water sources which ranged from 13 to 79 kg NO₃-N ha⁻¹ (12 to 71 lb N ac⁻¹). By incorporating the small grains in the vegetable and potato rotations, the systems had minimum net NO₃-N losses or were recovering NO₃-N from the underground water sources.

Other water-management tools. Other water-management approaches include water-table management and drainage ditch water-level management. Water-table management can be accomplished by design of tile drainage systems and by use of tile outlets as water-level control devices. Water-table management can affect leaching by altering the distribution of N between various soil N cycle pathways. Specifically, different water-table depths can change the aeration status of the soil, which will affect crop N recovery, leaching, and denitrification.

An example of the effect of water-table management on N leaching has been reported by Steenvoorden (1985), who summarized a three-year lysimeter study using liquid swine manure applied to a sandy soil and cropped to orchardgrass in the Netherlands. The spring water-table depths were controlled at 0.5, 1.0, or 1.5 m (20, 40, or 60 in), but summer water-table depths were all allowed to fall to 1.5 to 1.7 m (60 to 67 in) because of ET losses. The data showed that the 1.5 m (60 in) deep water table resulted in crop recoveries of 24%, leaching losses of 39%, and unaccounted-for losses (most likely denitrification) of 37%. The 1.0 m (40 in) deep water table produced crop recoveries of 28%, leaching losses of 27%, and unaccounted-for losses of 45%. The N budget for the 0.5 m (20 in) deep water table was: plant recovery, 35%; leaching, 5%; and unaccounted-for losses, 60%. These data show
that a shallow water table can lead to lower leaching losses, higher crop N recoveries, and higher unaccounted-for losses. Shallow management of the spring water table thus channeled as much as 60% of the N into denitrification for the carbon-rich manure source of this study, which resulted in a marked reduction of nitrate leaching.

Tile-line or drainage-ditch water management typically involves use of water-level control structures to change the water height in the ditches and water-table depth beneath adjacent fields. Water level is usually raised in the winter months to encourage poor aeration and promote denitrification. Controlled water-level studies have been reported from North Carolina by Gilliam et al. (1979), who studied drainage outflows from controlled-vs. uncontrolled-drainage fields, which included moderately well-drained soils and poorly drained soils. These studies reported a reduction in NO\textsubscript{3}-N movement through the tile lines of moderately well-drained soils from 25 to 40 kg N ha\textsuperscript{-1} (22 to 35 lbs N ac\textsuperscript{-1}) to 1 to 7 kg N ha\textsuperscript{-1} (1 to 6 lbs N ac\textsuperscript{-1}) with controlled drainage. The lower NO\textsubscript{3}-N losses are attributed to a lower tile-drainage volume. On poorly drained soils, controlled drainage resulted in a 50% reduction in NO\textsubscript{3}-N movement through drainage ditches because of a reduction in tile-flow. The reduction in tile outflow on these soils was accompanied by an increase in water movement into, and through, the deeper soil horizons. On well-drained (well-oxidized) soils, this increased percolation simply transported NO\textsubscript{3}-N through the soil, rather than through the tile lines. On poorly drained soils, the increased percolation resulted in increased N losses through denitrification because of the poor aerated status of the subsoils. However, the final impact on downstream water quality from these field water-level control studies could not be determined because of undocumented N transformation in the drainage canals and dilution along the drainage canals. Nonetheless, the data clearly demonstrate that water-level control techniques offer another avenue for management of N leaching, especially on poorly drained soils with slopes of less than 1%.

The above water-table management practices have specific geographic-hydrologic applications because of the limited areas with high water tables, poorly drained soils, and flat topography (e.g., the Atlantic Coastal Plain, Gulf Coast Plain, etc.). However, where water-table management is possible, it offers another tool for management of N leaching.

**On-site Monitoring of Nitrogen Status**

On-site monitoring of crop N status is a valuable method to avoid excess N additions and, therefore, reduce potential leaching losses. On-site monitoring methods can be grouped into an “in-season monitoring” class and a “real-time monitoring” class. Seasonal methods monitor the N status of the crop and include the pre-sidedress soil nitrate test (PSNT), the leaf chlorophyll meter (LCM), and plant-nitrate tests. Real-time methods include spectral reflectance measurements with remote sensing, coupled with modeling to forecast N needs of the crop in real time.

**In-season monitoring tools.** The PSNT is a commonly used soil test in the Northern Corn Belt and Northeast that measures the soil NO\textsubscript{3}-N concentration in the surface 30 cm (1 ft) of soil when corn is 20 to 30 cm (8 to 12 in) tall. Bundy and Meisinger (1994) have described the principles underlying the PSNT and the details of using the PSNT. Basically, the PSNT provides a timely monitoring of soil NO\textsubscript{3}-N pool, which has been shown to successfully identify N-sufficient sites and to provide guidance for sidedress fertilizer N recommendations. The ability of the PSNT to affect leaching has been evaluated by Guillard et al. (1999) on a Connecticut sandy loam growing silage corn using zero-tension pan lysimeters to monitor leaching. This two-year study compared fertilizer N management systems of a standard 196 kg N ha\textsuperscript{-1} (175 lbs N ac\textsuperscript{-1}) preplant application (no PSNT), a PSNT based system that received 90 kg N ha\textsuperscript{-1} (80 lbs N ac\textsuperscript{-1}) preplant with sidedress N determined by PSNT test, and a PSNT-based system that received all the N at sidedress. Flow-weighted NO\textsubscript{3}-N concentrations averaged 20 mg NO\textsubscript{3}-N L\textsuperscript{-1} (20 ppm) for the standard preplant treatment, 7 mg NO\textsubscript{3}-N L\textsuperscript{-1} (7 ppm) for the PSNT receiving preplant N, and 5 mg NO\textsubscript{3}-N L\textsuperscript{-1} (5 ppm) for the PSNT receiving all sidedress N. The corresponding quantities of N lost by leaching were 50, 19, and 15 kg N ha\textsuperscript{-1}, respectively (45, 17, and 13 lbs N ac\textsuperscript{-1}, respectively). Guillard et al. (1999) found no significant difference in corn yields among the three treatments, with average sludge dry matter (DM) yields being 16.5 Mg ha\textsuperscript{-1} (24 t ac\textsuperscript{-1} of 30% DM sludge). The main factor contributing to the leaching reduction was the avoidance of excess N applications, because the average fertilizer N rate was 196 kg N ha\textsuperscript{-1} (175 lbs N ac\textsuperscript{-1}) for the standard preplant, 113 kg N ha\textsuperscript{-1} (100 lbs N ac\textsuperscript{-1}) for the PSNT with preplant N, and 80 kg N ha\textsuperscript{-1} (71 lbs N ac\textsuperscript{-1}) for the sidedress N treatment.

The authors concluded that a properly calibrated PSNT could reduce excess fertilizer N, reduce nitrate leaching, and reduce the potential for nitrate contamination of groundwater. These results agree with a four-year study in Vermont (Durieux et al. 1995) that evaluated the PSNT vs. conventional manure-crop-history N-management systems, it concluded that the PSNT system reduced the levels of residual N after harvest and therefore reduced the potential for N leaching during winter. The PSNT was also evaluated in a five-year Midwest regional trial with more than 200 site-years of data (Bundy et al. 1999). This evaluation did not estimate N leaching but was based on a crop-response criterion. The study reported that the PSNT success rate for predicting a N response was 83% for the traditional 30 cm (1 ft) deep sample, but the success rate for a deeper 60 cm (2 ft) sample rose to 90%. Sampling to 60 cm (2 ft) also improved the success of predicting nonresponsive sites, because nitrate N in the 30 to 60 cm (1 to 2 ft) depth is readily available to corn; accounting for this deeper N should result in improved NUE and reduce the risk of N leaching.

A direct measure of crop N status can also provide very useful information for N management. However, plant N indexes are point-in-time measurements that reflect both N availability and the ability of the crop to convert photosynthate into protein or chlorophyll (affected by water stress, sunlight, growth stage, and other factors). The leaf chlorophyll meter (LCM) has been developed to monitor crop N status by Schepers et al. (1992a, 1992b) and Wood et al. (1992a, 1992b). The LCM uses a local N-sufficient area in the field as a comparison to standardize factors such as variety, growth stage, water stress, and sunlight conditions. The LCM reads the “greenness” of a small area of a specific leaf from the test area and compares this reading with the local N-sufficient plant leaf. The comparison of these readings has been used to indicate the need for fertilizer N (Peterson et al. 1993, Reeves et al. 1993). The LCM is especially useful in irrigated systems where water stress is small and readings can be taken throughout the growing season, with N added as needed through the sprinkler irriga-
tion. This approach is particularly advantageous if N levels can affect yield and crop quality. Delgado et al. (2001b) reported a correlation between the LCM and the yield and tuber quality of potato (production of larger tubers at harvest).

Other useful plant N tests are based on measurements of stalk or sap NO$_3$-N at a specific physiologic stage. These tests are used to detect N stress or N excess (Scaife and Stevens 1983, Blackmer et al. 1992). The tests have been carefully calibrated to interpret the NO$_3$-N concentration into a plant-N stress/excess category. The end-of-season stalk nitrate test was developed for corn by Binford et al. (1990). The test is based on the fact that NO$_3$-N can accumulate in the basal part of the corn stalk at maturity, if the plant has received sufficient or excess N. The timing of the test makes it a post mortem measure of N sufficiency/excess during the previous growing season. Blackmer et al. (1992) and Sims et al. (1995) have proposed an optimum concentration range of about 0.7 to 2.0 g NO$_3$-N kg$^{-1}$ (0.7 to 2.0 ppm); values below the optimum probably would have responded to additional N, while values above the optimum are considered excessive-N sites.

The NO$_3$-N concentration of plant sap (Scaife and Stevens 1983) has also been successfully used to identify N stress or excess in vegetable crops during the growing season. (See below.) Delgado et al. (2001b) reported a correlation between potato petiole NO$_3$-N content and the yield and tuber quality at harvest. There is potential to use this test to evaluate how N-management practices affect the in situ N status of the crop and its quality. Another use for sap NO$_3$-N tests is in systems that use scavenger crops for grazing. Winter cover crops can accumulate NO$_3$-N to levels that can be toxic to animals. Delgado and Follett (1998) reported that the sap NO$_3$-N test can be used to identify potential high levels of NO$_3$-N in winter cover crops that have scavenged residual NO$_3$-N and are intended for grazing.

Using in-field soil or plant N tests such as the PSNT, the LCM, or plant NO$_3$-N tests are valuable tools for identifying N-sufficient sites and avoiding excess N applications. Avoiding excess N inputs is one of the basic principles for managing N leaching.

Real-time monitoring tools. Real-time monitoring methods are the newest tools for managing N leaching (Delgado 2001b; Delgado et al. 2002). There is potential to use the spectral reflectance in remote sensing for N management (Stanhill et al. 1972, Al-Abbas et al. 1974). Remote sensing and spectral reflectance have permitted the development of several indexes that can be used to determine the crop N status during the growing season. For example, Bausch and Duke (1996) have developed the N reflectance Index (NRI) and Tucker (1979) the Normalized Difference Vegetation Index (NDVI) to directly monitor crop N status. These indexes can separate stressed vs. vigorous plants based on their reflectance in the green part of the spectrum (530 to 570 nm, 5300 to 5700 A) and in the near-infrared portion of the spectrum (780 to 850 nm, 7800 to 8500 A). These real-time monitoring tools offer the prospect for direct detection of N-stressed areas that can then be fertilized with site-specific N applicators to tailor N management to the precise needs of the crop in a specific area of the field. These tools can take much of the weather forecasting guesswork out of N management planning, resulting in improved NUE and subsequent reductions in N leaching.

Crop simulation models. Crop simulation models are powerful tools for managing N leaching. The Nitrogen Leaching and Economical Analyses Package (NLEAP, Shaffer et al. 1991) has been used to evaluate the effects of best management practices on N-use efficiencies, leaching, and NO$_3$-N dynamics (Beckie et al. 1994, Shaffer et al. 1995, Delgado et al. 2000 and 2001a, Hall et al. 2001). This model is capable of estimating the effects of various N-management scenarios such as rate and time of N application, crop rotations, irrigation strategies, and other N-management options on crop N uptake and potential N loss. A significant advantage of using models to evaluate management strategies is the fact that models can be run over several growing seasons to assess the long-term effect of various strategies. The primary purpose for NLEAP is to evaluate the likelihood for using specific best management practices to protect groundwater quality—i.e., manage N leaching. For example, Delgado (2001a) found that the NUE for irrigated small grains and deep-rooted crops was higher than shallow-rooted crops receiving higher N inputs. (See discussion below.) The NLEAP model can also be used to identify N hot spots in a field or across regions (Delgado 2001a, Hall et al. 2001).

Site-specific management. Site-specific management is another approach for applying several of the above tools (e.g., expected yield, soil water holding capacities, etc.) to discrete small-scale management zones through precision agriculture. The central component of site-specific management is the use of global positioning systems (GPS) to record the precise geographical locations of sampling and harvesting data. Geographic information systems (GIS) can store, organize, and manipulate large data sets of geographically defined data (e.g., soil properties, soil tests), as well as various agricultural operations that can impact N leaching (e.g., fertilizer application rates, irrigation rates). A new technology that is well-suited for GPS systems is the Veris® model 3100 sensor cart, which measures soil electrical conductivity (EC) (Lund et al. 1999). Traditional data resulting from in-season monitoring techniques (e.g., the PSNT, LCM, and plant NO$_3$-N tests) can also be used with GPS and GIS to identify areas of N sufficiency or deficiency. The application of GPS and GIS to long-term soil productivity properties (e.g., water-holding capacity, rooting depth, organic matter, etc.), previous management (e.g., crop history, previous yields, etc.), and recent yield-defining factors (e.g., rainfall/irrigation, crop water stress, etc.) should open the door to real-time site-specific N management.

Summary of Case Studies for Managing Nitrogen Leaching

Methods and materials. Irrigated cropping systems of south central Colorado have been monitored since 1992 on more than 30 farms involving more than 70 fields. Nitrogen and irrigation management practices have been collected with specific response studies conducted at some sites. Specific information about best management practices applied at these sites can be found in Ristau (1999) and Delgado (2001a). These studies have involved collaboration with Colorado State University, local farmers, the U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) and others to develop a Best Management Practices Bulletin for irrigated systems of south-central Colorado (Ristau 1999).

Management-practice information was collected at each site, including all N inputs, time of N application, and irrigation management. Soil chemical and physical properties were also measured and entered into the
NLEAP model. For additional information on how NLEAP simulations were conducted, see Delgado (1999, 2001a) and Delgado et al. (2000, 2001a). Yields, N uptake, and observed initial and final NO₃⁻N in the soil profile were also measured. Cooperating farmers followed the irrigation scheduling and N-management practices described in Ristau (1999). Irrigation scheduling accounted for ET, precipitation, and hydraulic properties at the sites. The NLEAP model was used to simulate residual soil NO₃⁻N, which was correlated with observed NO₃⁻N values. Center-pivot irrigation sprinklers were calibrated for accuracy, and the NO₃⁻N in irrigation water was measured and factored into the management system. Climatic data was collected from the nearest weather station, and local rain and/or snow was measured at each site.

Plant N dynamics at selected sites were monitored with the LCM (the SPAD® meter), plant sap NO₃⁻N tests (the Cardy® meter), and remote sensing. These data were collected within a GPS framework and summarized with GIS to assess the N and irrigation-management practices (Delgado et al. 2001b, 2002). Remote sensing images were acquired with a Duncan Tech MS3100 multispectral digital camera (Duncan Technologies) to monitor N status. This camera acquired data in the green, red, and near-infrared regions of the electromagnetic spectrum. Remote sensing images were acquired from an aerial platform and with flight navigation using MediaMapper software (Red Hen Systems Inc.). Image processing and analyses were done with ERDAS Imagine v8.4 (ERDAS Inc.) software. Ground control points were used for geo-rectification of the acquired images. Surface maps were created with SoilRx® and MapCalc (Red Hen Systems Inc, Fort Collins, CO).

**Results and discussion.** Figure 3 summarizes the water dynamics for a typical field, irrigation and rain inputs (dashed line) followed potential ET (solid line), which contributed to a small water surplus and a reduction of NO₃⁻N losses from the system. Although the average precipitation in this region is about 175 mm (7 in) per year, local thunderstorm events can contribute to leaching events from the root zone. Because there were differences in root depths between the deep-rooted barley and shallow-rooted potato, the available soil water for barley and potato were 40 mm (1.6 in) and 31 mm (1.25 in), respectively. The only precipitation event that was greater than 16 mm (0.65 in) during the two growing seasons shown in Figure 3 was 38 mm (1.5 in) early in the barley growing season (May 9), about one month after planting barley. At this time the available soil water was low, because barley root depth was shallow. For potato there were two local large rain events during the growing season, 40 mm (1.6 in) on July 3 and 35 mm (1.4 in) on Aug. 29. The first large precipitation event was before the close of potato canopy and the late August event occurred when the residual
soil NO₃-N susceptibility to leaching was high. The water inputs from the local thunderstorms were the driving force for NO₃-N leaching out of the root zone. However, the irrigation and N management practices kept NO₃-N leaching to a minimum, as discussed below.

Figure 4 summarizes the N dynamics for the same field and shows that NO₃-N leaching losses from the root zone were 24 and 72 kg NO₃-N ha⁻¹ (21 and 64 lb N ac⁻¹) for barley and potato, respectively. The NO₃-N leaching losses from the 1 m (3.2 ft) deep soil profile were 12 and 22 kg NO₃-N ha⁻¹ (11 and 20 lb N ac⁻¹) lower than those from the root zone. The NO₃-N applied with irrigation amounted to 27 and 21 kg NO₃-N ha⁻¹ (24 and 19 lb N ac⁻¹) for the barley and potato, respectively. For barley, the irrigation water NO₃-N was smaller than the amount leaching from the soil profile. Thus, the barley had a net effect of removing about 15 kg NO₃-N ha⁻¹ (13 lb NO₃-N ac⁻¹). The rotation of a deep-rooted small grain with a shallow-rooted vegetable crop promoted the scavenging of NO₃-N out of the lower soil depths, reduced net NO₃-N leaching, and contributed to the conservation of groundwater resources. Irrigation scheduling was a significant factor in reducing NO₃-N losses from the soil profile. Although the potato system had a net leaching loss of about 1 kg NO₃-N ha⁻¹ (1 lb NO₃-N ac⁻¹), the net effect for the rotation was an annual removal of about 7 kg NO₃-N ha⁻¹ (6.4 lb NO₃-N ac⁻¹). Therefore, the rotation of deep-rooted small grains with shallow-rooted crops contributed to the recovery of NO₃-N from ground water. Nitrogen use efficiency is correlated with root depth, and management practices that increase NUE will reduce N leaching from irrigated systems.

An important principle demonstrated in these studies is the need to apply N to irrigated systems with split applications, i.e., by sidedressing or by small additions through the irrigation system. Splitting N applications contributes to increase NUE, especially when N is applied at the time of greatest demand. These on-farm studies have also shown the value of monitoring the crop N status with measurements of petiole NO₃-N content on a dry matter basis, as recommended by Ristau (1999). The LCM and in situ NO₃-N test have been correlated with the dry-tissue test and are viable alternatives that farmers can use to monitor the in situ N status of these crops. The yield of irrigated barley was significantly correlated (r²=0.75) with both the LCM and sap NO₃-N readings.

The principles and concepts for managing N leaching discussed above can be further evaluated with new GIS and GPS software and technologies. There is potential to apply these principles and concepts to specific areas of the fields, or management zones. Figure 5 shows the spatial distribution of soil clay and residual soil NO₃-N to 60 cm (24 in). Figure 5 shows regions where the accumu-
tion of residual NO$_3$-N is correlated with soil texture (Delgado 1999, 2001b; Delgado and Duke 2000), although the correlation is not strong ($r^2$=0.29), it was significant at $P<0.001$. Delgado (1999) reported that the residual soil NO$_3$-N was higher in the finer-textured areas for three fields, before and after harvest of lettuce, potato and small grains. Farmers can take advantage of this correlation to construct N budgets by zones and apply the needed amounts of N that will contribute to high yields, better-quality crops and lower environmental impacts. Delgado et al. (2001b) reported the application of remote sensing technologies to monitor crop N status during the growing season. Figure 6 is an NDVI image of the center-pivot system, which shows areas that were correlated to the high concentrations of residual soil NO$_3$-N. These preliminary data (Figures 5 and 6) suggest that remote sensing technologies will be useful tools in defining areas with high N accumulation (higher N recoveries) and distinguishing them from areas with low N accumulation that are susceptible to higher NO$_3$-N leaching (Delgado 2001a; Delgado et al. 2001b, 2002). The NLEAP model was able to simulate the effects of management practices on the high and low N accumulation and NO$_3$-N leaching for these areas (Delgado 1999, 2001a). These high NO$_3$-N leaching areas can then be targeted for site-specific application of one or more of the above leaching-management techniques to reduce NO$_3$-N leaching. Additionally, by using management zones, accurate N budgets can be conducted for those areas of high N accumulation, reducing N applications and losses from the system.

**Case studies synopsis.** Irrigation scheduling and N management practices, such as N rates consistent with expected yield, split N applications, and accounting for soil NO$_3$-N, can increase NUE and reduce NO$_3$-N leaching. Use of crop rotations will also contribute to reduced N leaching. The use of N and irrigation best management practices minimized net losses of NO$_3$-N from the soil profile, which will protect groundwater quality. New sensing technologies combined with spatial statistics can monitor the crop N status and contribute to a further reduction of N leaching from irrigated fields.

**Summary and Conclusions**

Controlling N leaching presents a challenge to nutrient managers, who must develop N management plans that consider rate and application strategies that account for soil properties, hydrology, and crop-plant systems of a specific site. Major leaching events occur when soil N concentrations are high and water is moving through the soil profile. The universal tools for managing N leaching include understanding the soil-plant-hydrologic cycle, avoiding excess N applications, and applying N in phase with crop demand. Specific cropping system tools for managing leaching include use of grass cover crops, adding a legume to a rotation, and adding crops that more fully use the soil-water resources. The primary water-management tool to reduce N leaching is irrigation schedule.
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