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

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

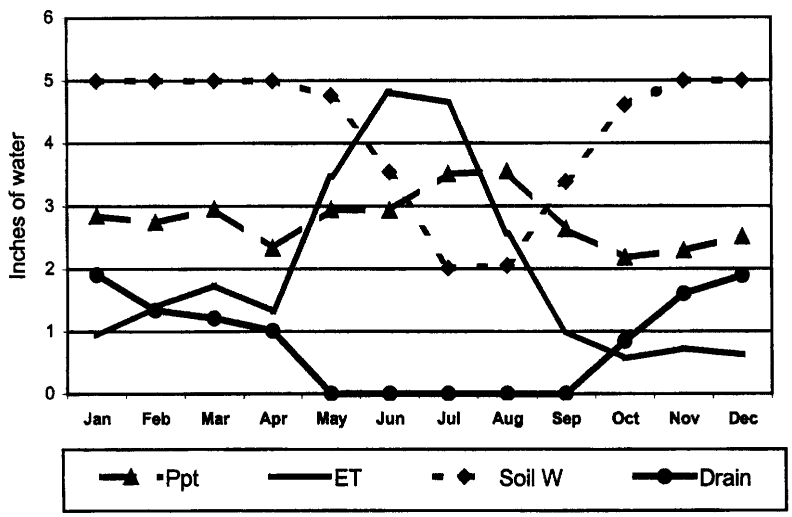
Controlling nitrogen (N) leaching presents a major challenge for nutrient managers. Nutrient management strategies regarding rate and time of N applications must be developed for the specific soils, hydrology, and crop-tillage systems of individual fields. However, leaching is only one of several outputs 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 (NO_3^-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, NO_3^-N can be converted to N_2 and N_2O gasses 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 NO_3^-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 NO_3^-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

John J. Meisinger and **Jorge A. Delgado** are with the U.S. Department of Agriculture's Agricultural Research Service. Meisinger is in Beltsville, Maryland, and Delgado is in Fort Collins, Colorado.

Figure 1

Humid region soil-crop-hydrologic cycle for a sandy loam soil growing corn in the Piedmont region of North Carolina showing precipitation (Ppt, triangles), corn evapotranspiration (ET, solid line), soil water content to 1 m (Soil W, diamonds), and drainage below 1 m (Drain, circles data adapted from Smith and Cassel (1991).



added in fertilizer and/or manure (Legg and Meisinger 1982, McNeil and Pratt 1978, Gast et al. 1978, Pratt 1984, Randall and Iragavarapu 1995). There is general agreement that nitrate leaching is a major avenue for N loss in humid regions and in irrigated agricultural systems (Legg and Meisinger 1982, Pratt 1984, Jemison and Fox 1994).

General principles. 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:

Leaching loss = (leachate volume) X (N concentration of leachate). (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 water-holding 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

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

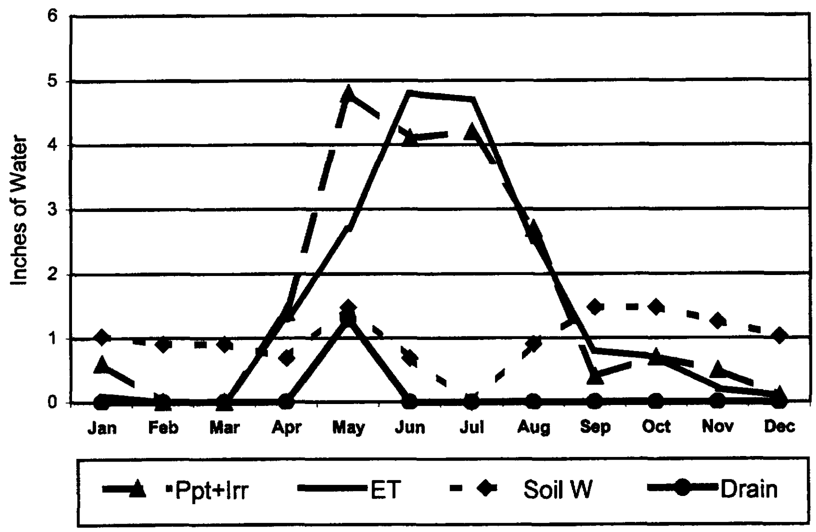
this arid climate should use practices that focus on both irrigation management and management of the soil N concentrations. Nitrate leaching below the root zone can also occur in the dryland agriculture of the Great Plains, especially for traditional cropping systems (e.g., wheat (*Triticum aestivum 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 NO_3^--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.

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. (2001a).



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 NO_3^--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

Table 1. Common factors considered in nutrient recommendation programs.

Factor	Some typical approaches for including factor in recommendation
Expected yield	Average yield over 5 years omitting drought years; average yield plus 10%
Legume credit	Alfalfa credited with 50-100 kg N ha^{-1}; soybean credit 30-50 kg N ha^{-1}
Manure credit	Manure total N and NH_4-N analysis, plus manure application method
Profile nitrate	Direct analysis of 90 cm soil sample for NO_3-N
Irrigation N	Direct analysis of irrigation water
Other factors	Soil pre-sidedress NO_3-N analysis; adjust for time of application (pre-plant vs. sidedress); adjust for additives (e.g., nitrification inhibitor)

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

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 Cassel (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 leaching 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.

Cropping System Tools for Managing Leaching

Employing a systematic rotation of crops or using special purpose crops is a well-established method of managing leaching. The goal is to add crops that lead to a more complete utilization of the soil and water resources and/or to add a crop that provides active N uptake when the soil would otherwise be bare. For example, the addition of crops with deeper root zones, lower fertilizer inputs, longer growing seasons, tolerance to salinity or water stress, or the addition of scavenger crops to use residual N.

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 NO_3^-N concentrations of 32 mg NO_3^-N L^{-1} (32 ppm) for continuous corn (C-C) and 24 mg NO_3^-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 (NO_3^-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 NO_3^-N L^{-1} (30 ppm) for C-C, compared with 14 mg NO_3^-N L^{-1} (14 ppm) for C-Sb. Corresponding total NO_3^-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 NO_3^-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 NO_3^-N L^{-1} (4 ppm) below alfalfa compared with 15 mg NO_3^-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 NO_3^-N L^{-1} (32 ppm), while alfalfa drain effluent averaged 3 mg NO_3^-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 NO_3^-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 NO_3^-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 NO_3^-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 NO_3^-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 NO_3^-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 cereals (e.g., corn or wheat) rather than low-N demand legumes (e.g., field beans (*Phaseolus vulgaris L.*)). Meek 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 systems' 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

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

(2001a) reported a correlation between the depths of rooting systems, NO_3^-N leaching and N-use efficiencies (NUE). Shallow-rooted vegetable crops are prone to higher leaching losses (lower NUE) than deep-rooted cereal crops. Nitrate-leaching losses from shallow-rooted vegetable crops grown on irrigated sandy soils in Colorado were 75 kg N ha^{-1}, (67 lb N ac^{-1}) higher than those for small grains, which lost 29 kg N ha^{-1} (26 lb N ac^{-1}) (Delgado 2001a). The higher NO_3^-N leached from the vegetables was a function of rooting depths, amount of leachate, and N inputs. Delgado (2001a) estimated that leaching losses for the vegetables amounted to 19% of the total N input of 254 kg N ha^{-1} (227 lb N ac^{-1}), while corresponding leaching losses for the small grains was 10% of the total N input of 146 kg N ha^{-1} (130 lb N ac^{-1}). Thus, the addition of a deep-rooted crop, such as barley, into a potato (*Solanum tuberosum L.*) system can improve the NUE with concomitant reductions in nitrate leaching (Delgado et al. 2001a). Another example of reduced leaching from improved exploitation of soil-water resources has been summarized by Westfall et al. (1996), who state that nitrate leaching from the traditional wheat-fallow system of the Great Plains can be reduced by shifting to a more intense wheat-sorghum-fallow system, which shortens the fallow period and allows greater use of stored water. Baligar et al. (2001) has reported that NUE can be significantly increased with deep-rooted varieties, aluminum tolerant varieties, or salt tolerant varieties.

Add a scavenger crop to a cropping system. Adding a cover crop or other scavenger crop to a system is a longstanding method to reduce leaching. A cover crop can reduce leaching by converting mobile NO_3^-N into immobile plant protein and thereby lower the soil NO_3^-N concentration during the leaching season. Another important benefit of cover crops is their potential for soil and water conservation (Dabney et al. 2001). The effects of cover crops on nitrate leaching have been reviewed by Meisinger et al. (1991) and the advantages/disadvantages of covers have been summarized by Dabney et al. (2001). Both of these reviews concluded that cover crops were a greatly under-used resource. Meisinger et al. (1991) concluded that cover crops can commonly reduce both the mass of N leached and the NO_3^-N concentration in the leachate by 20% to 80%. 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 use of nonagronomic 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 1-2 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 agriculture 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. Dinnes 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

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

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, southeastern 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. (1997b) 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 prospect 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 prospect 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 NI) 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

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

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 (Rangely 1987, Bucks 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 system, 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 Hergert (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 NO_3^-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 NO_3^-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 Ferguson 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 NO_3^-N concentration, amount of irrigation, and soil NO_3^-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, NO_3^-N background in irrigation water, and initial and final residual inorganic NO_3^-N and NH_4-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 NO_3^-N out of the soil profile (0 to 0.9 m) (0 to 36 in) that ranged from 5 to 12 kg NO_3^-N ha^{-1} (5 to 11 lb N ac^{-1}). For deeper-rooted crops, such as small grains, there was a net recovery of NO_3^-N from underground water sources which ranged from 13 to 79 kg NO_3^-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 NO_3^-N losses or were recovering NO_3^-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 devises. 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

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

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_3^-N movement through the tile lines of moderately well-drained soils from 25 to 40 kg N ha^{-1} (22 to 35 lbs N ac^{-1}) to 1 to 7 kg N ha^{-1} (1 to 6 lbs N ac^{-1}) with controlled drainage. The lower NO_3^-N losses are attributed to a lower tile-drainage volume. On poorly drained soils, controlled drainage resulted in a 50% reduction in NO_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_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_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_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^{-1} (175 lbs N ac^{-1}) preplant application (no PSNT), a PSNT based system that received 90 kg N ha^{-1} (80 lbs N ac^{-1}) preplant with sidedress N determined by PSNT test, and a PSNT-based system that received all the N at sidedress. Flow-weighted NO_3^-N concentrations averaged 20 mg NO_3^-N L^{-1} (20 ppm) for the standard preplant treatment, 7 mg NO_3^-N L^{-1} (7 ppm) for the PSNT receiving preplant N, and 5 mg NO_3^-N L^{-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^{-1}, respectively (45, 17 and 13 lbs N ac^{-1}, respectively). Guillard et al. (1999) found no significant difference in corn yields among the three treatments, with average silage dry matter (DM) yields being 16.5 Mg ha^{-1} (24 t ac^{-1} of 30% DM silage). 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^{-1} (175 lbs N ac^{-1}) for the standard preplant, 113 kg N ha^{-1} (100 lbs N ac^{-1}) for the PSNT with preplant N, and 80 kg N ha^{-1} (71 lbs N ac^{-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-

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

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 excesses (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 8500A). 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 need 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®[a] 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, the 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

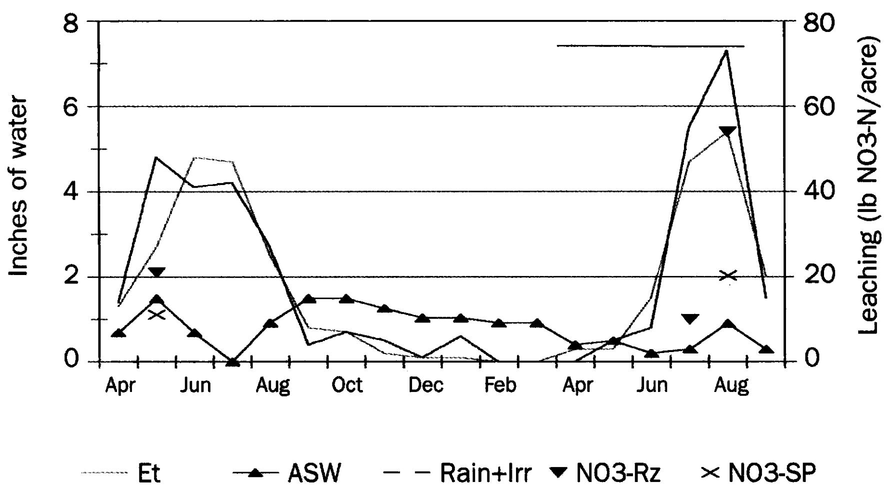
Methods and materials. Irrigated cropping systems of south central Colorado have been monitored since 1992 on more than 30 farms involving more than 70 fields. Nitrogen and irrigation management practices have been collected with specific response studies conducted at some sites. Specific information 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

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

Figure 3

NLEAP simulation of water dynamics for a center-pivot irrigated barley and potato rotation. Simulated evapotranspiration (ET), available soil water (ASW), and observed Rain + Irrigation inputs (Rain + Irr) are shown. The nitrate leached from the root zone (NO3-N LRZ) for these shallower (potato) and deeper-rooted (barley) crops, as well as from a similar soil depth of the soil profile (NO3-N LSP), were simulated. (For additional information on simulations from multiple soil depths see Delgado et al. [2000].)



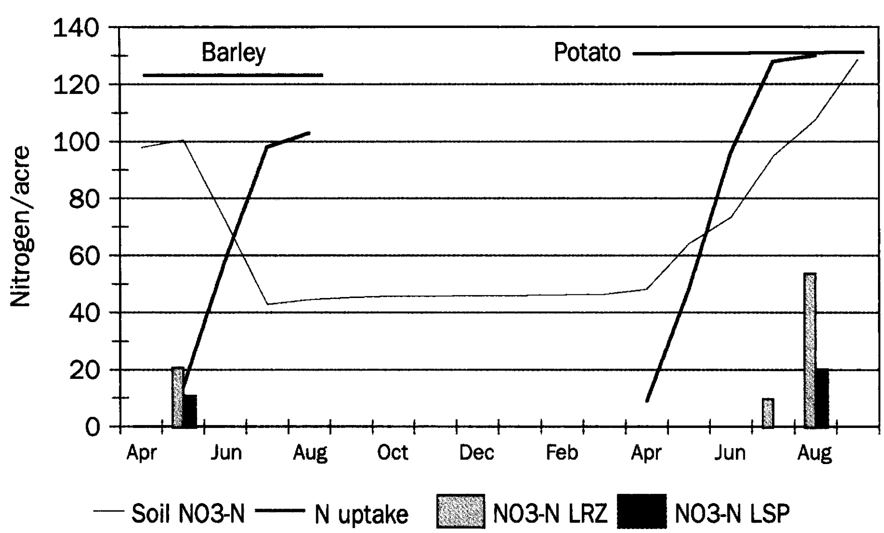
NLEAP model. For additional information on how NLEAP simulations were conducted, see Delgado (1999, 2001a) and Delgado et al. (2000, 2001a). Yields, N uptake, and observed initial and final NO_3^-N in the soil profile were also measured. Cooperating farmers followed the irrigation scheduling and N-management 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 NO_3^-N values. Center-pivot irrigation sprinklers were calibrated for accuracy, and the NO_3^-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 NO_3^-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 NO_3^-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

Figure 4

NLEAP simulated the N dynamics in a center-pivot irrigated barley and potato rotation. The nitrate leaching from the root zone (NO3-N LRZ) for these shallower (potato) and deeper-rooted (barley) crops, as well as from a similar soil depth (NO3-N LSP), were simulated. (For additional information on simulations from multiple soil depths, see Delgado et al. [2000].)



Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

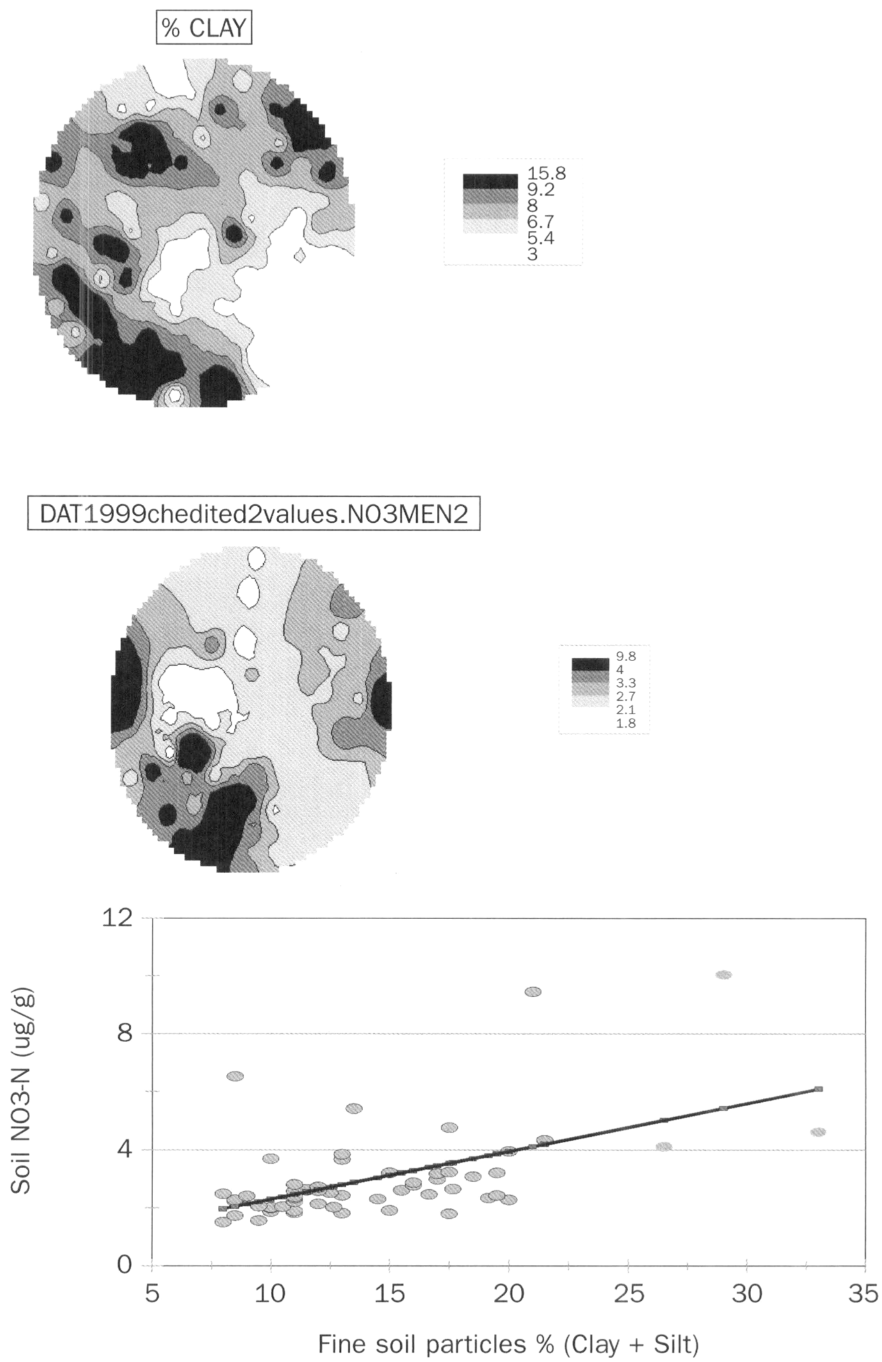
soil NO_3^-N susceptibility to leaching was high. The water inputs from the local thunderstorms were the driving force for NO_3^-N leaching out of the root zone. However, the irrigation and N management practices kept NO_3^-N leaching to a minimum, as discussed below.

Figure 4 summarizes the N dynamics for the same field and shows that NO_3^-N leaching losses from the root zone were 24 and 72 kg NO_3^-N ha^{-1} (21 and 64 lb N ac^{-1}) for barley and potato, respectively. The NO_3^-N leaching losses from the 1 m (3.2 ft) deep soil profile were 12 and 22 kg NO_3^-N ha^{-1} (11 and 20 lb N ac^{-1}) lower than those from the root zone. The NO_3^-N applied with irrigation amounted to 27 and 21 kg NO_3^-N ha^{-1} (24 and 19 lb N ac^{-1}) for the barley and potato, respectively. For barley, the irrigation water NO_3^-N was smaller than the amount leaching from the soil profile. Thus, the barley had a net effect of removing about 15 kg NO_3^-N ha^{-1} (13 lb NO_3^-N ac^{-1}). The rotation of a deep-rooted small grain with a shallow-rooted vegetable crop promoted the scavenging of NO_3^-N out of the lower soil depths, reduced net NO_3^-N leaching, and contributed to the conservation of groundwater resources. Irrigation scheduling was a significant factor in reducing NO_3^-N losses from the soil profile. Although the potato system had a net leaching loss of about 1 kg NO_3^-N ha^{-1} (1 lb NO_3^-N ac^{-1}), the net effect for the rotation was an annual removal of about 7 kg NO_3^-N ha^{-1} (6.4 lb NO_3^-N ac^{-1}). Therefore, the rotation of deep-rooted small grains with shallow-rooted crops contributed to the recovery of NO_3^-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 NO_3^-N content on a dry matter basis, as recommended by Ristau (1999). The LCM and in situ NO_3^-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 (r^2>0.75) with both the LCM and sap NO_3^-N readings.

Figure 5

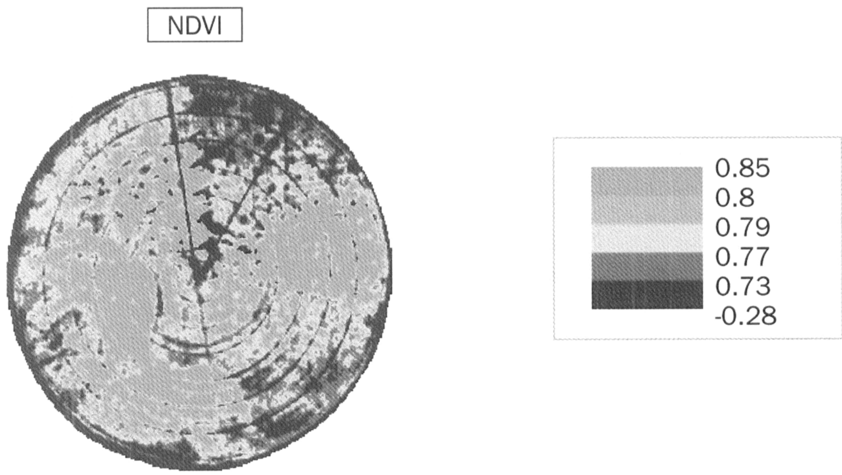
Spatial variability of clay (a), soil and NO3-N for the surface o to o.6 m (b) and correlation between fine particles (clay and silt) and soil NO3-N (c) of a center-pivot irrigated of south-central Colorado.



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 NO_3^-N to 60 cm (24 in). Figure 5 shows regions where the accumula-

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

Figure 6
Spatial variability of NDVI of a barley center-pivot irrigated of south-central Colorado.



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-tillage 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-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 use 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, 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 and the Normalized Difference Vegetation Index, can be combined with GPS and GIS 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, as well as to 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 a field, will improve crop N recoveries with subsequent reductions in N leaching.

Endnotes

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

References Cited

Al-Abbas, A.H., R. Barr, J.D. Hall, F.L. Crane, and M.F. Baumgardner. 1974. Spectra of normal and nutrient-deficient maize leaves. Agronomy Journal 66:16-20.

Baker, J.L., T.S. Colvin, S.J. Marley, and M. Dawelbeit. 1989. A point-injector applicator to improve fertilizer management. Applied Engineering in Agriculture 5:334-338.

Baligar, V.C., N.K. Fageria, and Z.L. He. 2001. Nutrient use efficiency in plants. Communications in Soil Science and Plant Analysis 32:921-950.

Bausch, W.C., and H.R. Duke. 1996. Remote sensing of plant nitrogen status in corn. Transactions American Society of Agriculture Engineers 39:1869-1875.

Beckie, H.J., A.P. Moulin, C.A. Campbell, and S.A. Brandt. 1994. Testing effectiveness of four simulation models for estimating nitrates and water in two soils. Canadian Journal of Soil Science 74:135-143.

Binford, G.D., A.M. Blackmer, and N.M. El-Hout. 1990. Tissue test for excess nitrogen during corn production. Agronomy Journal 82:124-129.

Blackmer, A.M., T.F. Morris, and G.D. Binford. 1992. Predicting nitrogen fertilizer needs for corn in humid climates: advances in Iowa. Pp. 57-72. In: B.R. Bock and K.R. Kelley (eds.). Predicting nitrogen fertilizer needs for corn in humid regions. Proceedings of Soil Science Society America Symposium held in Denver, Colorado, Oct. 28, 1991. Tennessee Valley Authority Bulletin Y-226, Muscle Shoals, AL.

Boyd, P.M, H.M. Hanna, J.L. Baker, M. White, and T.S. Colvin. 2000. Field evaluation of anhydrous ammonia

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

distribution manifolds. American Society of Agriculture Engineers paper 001140 at American Society Agriculture Engineers International meeting held in Milwaukee Wisconsin. ASAE, St. Joseph, MI.

Broadbent, F.E., and A.B. Carlton. 1978. Field trials with isotopically labeled nitrogen fertilizer. Pp. 1-41. In: D.R. Nielsen and J. G. MacDonald (eds.). Nitrogen in the environment. Vol. I. Nitrogen behavior in field soil. Academic Press, New York.

Buchleiter, G.W., H.R. Duke, and D.F. Heermann. 1992. Evapotranspiration theory: the meteeorologic and agronomic theory incorporated in the computation of evapotranspiration by the USDA-ARS program SCHED. United States Department of Agriculture-Agriculture Research Service, Fort Collins, CO.

Bucks, D.A., T.W. Sammis, and G.L. Dickey. 1990. Irrigation for arid areas. Pp. 499-548. In: G.J. Hoffman, T.A. Howell, and K.H. Solomon (eds.). Management of farm irrigation systems. ASAE, St. Joseph, MI.

Bundy, L.G., and J.J. Meisinger. 1994. Nitrogen availability indices. Pp. 951-984. In: R.W. Weaver (ed.). Methods of soil analysis: biochemical and microbiological properties. Soil Science Society of America Monogr. No. 5. Soil Science Society of America (SSSA), Madison, WI.

Bundy, L.G., D.T. Walters, and A.E. Olness. 1999. Evaluation of soil nitrate tests for predicting corn nitrogen response in the North Central region. North Central Regional Research Publication 342. Wisconsin Agriculture Experiment Station, Madison, WI.

Cameron, K.C., and A. Wild. 1984. Potential aquifer pollution from nitrate leaching following the plowing of temporary grassland. Journal of Environmental Quality 13:274-278.

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

Dahnke, W.C., and G.V. Johnson. 1990. Testing soils for available nitrogen. Pp. 127-140. In: R.L. Westerman (ed.). Soil testing and plant analysis, 3rd ed.. Soil Science Society of, Madison, WI.

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

Delgado, J.A. 1999. NLEAP simulation of soil type effects on residual soil nitrate-nitrogen in the San Luis Valley and potential use for precision agriculture. Pp. 1367-1378. In: P.C. Robert, R.H. Rust, and W.E. Larson (eds.). Proceedings fourth international conference on precision agriculture. American Society of Agronomy (ASA), Madison, WI.

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

Delgado, J.A. 2001b. Potential use of innovative nutrient management alternatives to increase nutrient use efficiency, reduce losses, and protect soil and water quality. Special issue of Journal Communication Soil Science and Plant Analysis. Marcel Dekker Inc., New York.

Delgado, J.A., and R.F. Follett. 1998. Sap test to determine nitrate-nitrogen concentrations in aboveground biomass of winter cover crops. Communications in Soil Science and Plant Analysis 29:545-559.

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

Delgado, J.A., and H.R. Duke. 2000a. Potential use of precision farming to improve nutrient management on irrigated potato-barley rotation. CDROM. In: P.C. Robert (ed.). Proceedings fifth international conference on precision agriculture. ASA, Madison, WI.

Delgado, J.A., R.F. Follett, and M.J. Shaffer. 2000b. Simulation of nitrate-nitrogen dynamics for cropping systems with different rooting depths. Soil Science Society of America Journal 64: 1050-1054.

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

Delgado, J.A., R.J. Ristau, M.A. Dillon, H.R. Duke, A Stuebe, R.F. Follett, M.J. Shaffer, R.R. Riggenbach, R.T. Sparks, A. Thompson, L.M. Kawanabe, A. Kunugi, and K. Thompson. 2001b. Use of innovative tools to increase nitrogen use efficiency and protect environmental quality in crop rotations. Communications in Soil Science and Plant Analysis 32:1321-1354.

Delgado, J., W. Colon, W. Bausch, D. Wright, D. Westfall, M. Dillon, A. Thompson-Johns, M. Shaffer, K. Thompson, H. Duke, R. Follett, and L J. Olivieri. 2002. Use of innovative tools to increase nitrogen use efficiency and protect environmental quality for temperate and tropical regions. Journal of Storm Waters 3(3):48-56.

Dinnes, D.L., D.L. Karlen, D.B. James, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. Agronomy Journal 94:153-171.

Durieux, R.P., H.J. Brown, E.J. Stewart, J.Q. Zhoa, W.E. Jokela, and F.R. Magdoff. 1995. Implications of nitrogen management strategies for nitrate leaching potentials: role of nitrogen source and fertilizer recommendation system. Agronomy Journal 87:884-887.

Evans, S.D., G.A. Pererson, D.T. Westfall, and E. McGee. 1994. Nitrate leaching in dryland agroecosystems as influenced by soil and climate gradients. Journal of Environmental Quality 23:999-1005.

Ferguson, R.B., C.A. Shapiro, G.W. Hergert, W.L. Kranz, N.L. Kloncke, and D.H. Krull. 1991. Nitrogen and irrigation management practices to minimize nitrate leaching from irrigated corn. Journal of Production Agriculture 4:186-192.

Follett, R.F., G.A. Reichman, E.J. Doering, and L.C. Benz. 1973. A nomograph for estimating evapotranspiration. Journal of Soil and Water Conservation 28:90-92.

Francis, G.S. 1995. Management practices for minimizing nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. Journal of Contaminant Hydrology 20:313-327.

Gast, R.G, W.W. Nelson, and G.W. Randall. 1978. Nitrate accumulation in soils and loss in tile drainage following nitrogen application to continuous corn. Journal of Environmental Quality 7:258-261.

Gilliam, J.W., R.W. Skaggs, and S.B. Weed. 1979. Drainage control to diminish nitrate loss from agricultural fields. Journal of Environmental Quality 8:137-142.

Guillard, K., T.F. Morris, and K.L. Kopp. 1999. The pre-sidedress soil nitrate test and nitrate leaching from corn. Journal Environmental Quality 28:1845-1852.

Hall, M.D., M.J. Shaffer, R.M. Waskom, and J.A. Delgado. 2001. Regional nitrate leaching variability: What makes a difference in northeastern Colorado. Journal of American Water Resource Association 37:139-150.

Hanna, H.M., M.L. White, T.S. Colvin, and J.L. Baker. 1999. Anhydrous ammonia distribution during field application. American Society of Agriculture Engineers Paper MC99-123. Proceedings 1999 ASAE Mid-Central meeting held in Saint Joseph Missouri, April 30-May 1, 1999. ASAE, St. Joseph, MI.

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

Jacobs, T.J., and J.W. Gilliam. 1985. Riparian losses of nitrate from agricultural drainage waters. Journal of Environmental Quality 14:472-478.

Jemison, J.M., and R.G. Fox. 1994. Nitrate leaching from nitrogen-fertilized and manured corn measured with zero-tension pan lysimeters. Journal of Environmental Quality 23:337-343.

Jensen, M.E., and H.R. Haise. 1963. Estimating evapotranspiration from solar radiation. Journal of Irrigation and Drainage Division. American Society Civil Engineers (ASCE) 89(IR):15-41.

Jensen, M.E., R.D. Burman, and R.G. Allen (eds.). 1990. In: Evapotranspiration and irrigation water requirements. American Society Civil Engineers Manuals and Reports on Engineering Practice No. 70. ASCE, New York.

Kanwar, R.S., T.S. Colvin, and D.L. Karlen. 1997. Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. Journal of Production Agriculture 10:227-234.

Legg, J.O., and J.J. Meisinger. 1982. Soil nitrogen budgets. Pp. 503-566. In: F.J. Stevenson et al. (eds.). Nitrogen in agricultural soils. Agronomy No. 22. ASA, Madison, WI.

Lorenz, J., and I. Broner. 2001. CROPFLEX 2000 - A crop management system user's manual. Colorado State University. Department of Chemistry and Bioresource Engingeering, Fort Collins, CO.

Lowrance, R.R., R.L. Todd, and L.E. Asmussen. 1984. Nutrient cycling in an agricultural watershed: streamflow and artificial drainage. Journal of Environmental Quality 13:27-32.

Lund, E.D., P.E. Colin, D. Christy, and P.E. Drummond. 1999. Applying soil electrical conductivity technology to precision agriculture. Pp. 1089-1100. In: P.C. Robert, R.H. Rust, and W.E. Larson (eds.). Proceedings fourth international conference on precision agriculture. ASA, Madison, WI.

McNeil, B.L., and P.F. Pratt. 1978. Leaching of nitrate from soils. Pp. 195-230. In: P.F. Pratt (ed.). Proceedings national conference on management of nitrogen in irrigated agriculture, held in Sacramento, California. May 15-18, 1978. University of California, Riverside, CA.

Meek, B.D., D.L. Carter, D.T. Westermann, J.L. Wright, and R.E. Peckenpaugh. 1995. Nitrate leaching under furrow irrigation as affected by crop sequence and tillage. Soil Science Society of America Journal 59:204-210.

Meisinger, J.J. 1984. Evaluating plant-available nitrogen in soil-crop systems. Pp. 391-416. In: R.D. Hauck et al. (eds.). Nitrogen in crop production. ASA, Madison, WI.

Meisinger, J.J., W.L. Hargrove, R.B. Mikkelsen, J.R. Williams, and V.W. Benson. 1991. Effect of cover crops on groundwater quality. Pp. 57-68. In: W.L. Hargrove (ed.). Cover crops for clean water. Proceedings of international conference on cover crops for clean water, held in Jackson, Tennessee, April 9-11, 1991. Soil and Water Conservation Society of America, Ankeny, IA.

Owens, L.B. 1987. Nitrate leaching losses from monolith lysimeters as influenced by nitrapyrin. Journal of Environmental Quality 16:34-38.

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org

Owens, L.B., W.M. Edwards, and M.J. Shipitalo. 1995. Nitrate leaching through lysimeters in a corn-soybean rotation. Soil Science Society of America Journal 59:902-907.

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

Penman, H.L. 1963. Vegetation and hydrology. 125 pp. Technical communication No. 53. Commonwealth Bureau of soils, Harpenden.

Peterjohn, W.T. and D.T. Correll. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466-1475.

Peterson, T.A., T.M. Blackmer, D.D. Francis, and J.S. Schepers. 1993. Using a chlorophyll meter to improve N management, Neb-Guide No. G93-1171-A. University of Nebraska Cooperative Extension Service, Lincoln, NE.

Power, J.F., and J.S. Schepers. 1989. Nitrate contamination of groundwater in North America. Agriculture Ecosystems and the Environment 26:165-187.

Power, J.F., A.D. Flowerday, R.A. Wiese, and D.G. Watts. 1998. Agricultural nitrogen management to protect water quality, USDA-CSREES-IDEA bulletin 4. Cooperative State Research Extension and Education Service, Washington, D.C.

Pratt, P.F. 1984. Nitrogen use and nitrate leaching in irrigated agriculture. Pp. 319-333. In: R.D. Hauck et al. (eds.). Nitrogen in crop production. ASA, Madison, WI.

Randall, G.W., and D.J. Mulla. 2002. Nitrate-N in surface waters as influenced by climatic conditions and agricultural practices. Journal of Environmental Quality 30:337-344.

Randall, G.W., and T.K. Iragavarapu. 1995. Impact of long-term tillage systems for continuous corn and nitrate leaching to tile drainage. Journal of Environmental Quality 24:360-366.

Randall, G.W., D.R. Huggins, M.P. Russelle, D.J. Fuchs, W.W. Nelson, and J.L. Anderson. 1997a. Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. Journal of Environmental Quality 26:1240-1247.

Randall, G.W., T.K. Iragovarapu, and B.R. Bock. 1997b. Nitrogen application methods and timing for corn after soybean in a ridge-tillage system. Journal of Production Agriculture 10:300-307.

Randall, G.W., G.L. Malzer, and B.W. Anderson. 1992. Nitrate losses to tile drainage as affected by nitrogen fertilization of corn in a corn-soybean rotation. Field research in soil science at university of Minnesota Southern Experiment Station. University of Minnesota Southern Experiment Station, Waseca, MN.

Rangely, W.R. 1987. Irrigation and drainage in the world. Pp. 29-35. In: W.R. Jordan (ed.). Proceedings of water and water policy in world food supplies, conference held in College Station, Texas. Texas Agriculture and Mining University Press, College Station, TX.

Reeves, D.W., P.L. Mask, C.W. Wood, and D.P. Delaney. 1993. Determination of wheat nitrogen status with a hand-held chlorophyll meter. Journal of Plant Nutrition 16:781-796.

Ressler, D.E, R. Horton, J.L. Baker, and T.C. Kaspar. 1997. Testing a nitrogen fertilizer applicator designed to reduce leaching losses. Applied Engineering in Agriculture 13:345-350.

Ressler, D.E, R. Horton, J.L. Baker, and T.C. Kaspar. 1998. Evaluation of localized compaction and doming to reduce anion leaching losses using lysimeters. Journal of Environmental Quality 27: 910-916.

Ristau, R.J. (ed.). 1999. Best management practices for nutrient and irrigation management in the San Luis Valley. Colorado State University Cooperative Extension Service Bulletin. Pp. 14. Cooperative Extension Service, Fort Collins, CO.

Sanchez, C.A., and A.M. Blackmer. 1988. Recovery of anhydrous ammonia-derived nitrogen-15 during three years of corn production in Iowa. Agronomy Journal 80:102-108.

Scaife, A., and K.L. Stevens. 1983. Monitoring sap nitrate in vegetable crops: comparison of test strips with electrode methods, and effects of time of day and leaf position. Communication in Soil Science and Plant Analysis 14:761-771.

Shaffer, M.J., A.D. Halvorson, and F.J. Pierce. 1991. Nitrate leaching and economic analysis package (NLEAP): Model description and application. Pp. 285-232. In: R.F. Follett, D.R. Keeney and R.M. Cruse (eds.). Managing nitrogen for groundwater quality and farm profitability. Proceedings of Symposium of American Society of Agronomy, held in Anaheim California, Nov. 30, 1988. SSSA-ASA, Madison, WI.

Shaffer, M.J., B.K. Wylie, and M.D. Hall. 1995. Identification and mitigation of nitrate leaching hot spots using NLEAP-GIS technology. Journal of Contaminate Hydrology 20:253-263.

Shaffer, M.J., and J. Delgado 2001. Field techniques for modeling nitrogen management. Pp. 391-411 In: R.F. Follett and J.L. Hatfield (eds.). Nitrogen in the environment: sources, problems and management. Elsevier Applied Science Publication, New York.

Schepers, J.S., T.M. Blackmer, and D.D. Francis. 1992a. Predicting N fertilizer needs for corn in humid regions: using chlorophyll meters. Pp. 105-114. In: B.R. Bock and K.R. Kelley (eds.). Predicting nitrogen fertilizer needs for corn in humid regions. Proceedings of Soil Science Society America Symposium held in Denver, Colorado, Oct. 28, 1991. Tennessee Valley Authority Bulletin Y-226, Muscle Shoals, AL.

Schepers, J.S., D.D. Francis, M. Vigil, and F.E. Below. 1992b. Comparison of corn leaf nitrogen and chlorophyll meter readings. Communications in Soil Science and Plant Analysis 23:2173-2187.

Sharpley, A., J.J. Meisinger, A. Breeuwsma, J.T. Sims, T.C. Daniel, and J.S. Schepers. 1998. Impacts of animal manure management on ground and surface water quality. Pp. 173-242. In: J.L. Hatfield (ed.). Animal waste utilization: effective use of manure as a soil resource. Ann Arbor Press, Chelsea, MI.

Shipley, P.S., J.J. Meisinger, and A.M. Decker. 1992. Conserving residual corn fertilizer nitrogen with winter cover crops. Agronomy Journal 84:869-876.

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

Sims, J.T., B.L. Vasilas, K.L. Gartley, B. Milliken, and V. Green. 1995. Evaluation of soil and plant nitrogen tests for maize on manured soils of the Atlantic Coastal Plain. Agronomy Journal 87:213-222.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: historical perspective and current research. Journal of Environmental Quality 27:277-293.

Smith, S.J., and D.K. Cassel. 1991. Estimating nitrate leaching in soil materials. Pp. 165-188. In: R.F. Follett, D.R. Keeney and R.M. Cruse (eds.). Managing nitrogen for groundwater quality and farm profitability. Proceedings of Symposium of American Society of Agronomy, held in Anaheim, California, Nov. 30, 1988. SSSA-ASA, Madison, WI.

Stanhill, G., V. Kalkofi, M. Fuchs, and Y Kagan. 1972. The effects of fertilizer applications on solar reflectance from a wheat crop. Israel Journal of Agriculture Research 22:109-118.

Steenvoorden, J.H.A.M. 1985. Nutrient leaching losses following application of farm slurry and water quality considerations in the Netherlands. Pp. 168-176. In: A. Dam Kofoed et al. (eds). Efficient land use of sludge and manure. Proceedings of round-table seminar on efficient land use of sludge and manure, Commission European Communities Environmental Research Program, held in Brorup-Askov, Denmark, June 25-27, 1985. Elsevier Applied Science Publication, New York.

Stehouwer, R.C., and J.W. Johnson. 1990. Urea and anhydrous ammonia management for conventional tillage corn production. Journal of Production Agriculture 3:507-513.

Stevenson, F.J. 1982. Humus chemistry genesis, composition and reactions. John Wiley and Sons Inc., New York.

Timmons, D.R., and A.S. Dylla. 1981. Nitrogen leaching as influenced by nitrogen management and supplemental irrigation level. Journal of Environmental Quality 10:421-426.

Timmons, D.R. 1984. Nitrate leaching as influenced by water application level and nitrification inhibitors. Journal of Environmental Quality 13:305-3309.

Tisdale, S.L., and W.L. Nelson. 1975. Soil fertility and fertilizers. Macmillan Publishing Company Inc., New York.

Toth, J.D., and R.H. Fox. 1998. Nitrate losses from a corn-alfalfa rotation: lysimeter measurement of nitrate leaching. Journal of Environmental Quality 27:1027-1033.

Tribe, D. 1994. Feeding and greening the world, the role of agricultural research. 274 pp. Commonwealth Agriculture Bureau, Wallingford.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing and the Environment 8:127-150.

United State Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS). 2000. Summary Report 1997 National Resources Inventory (revised December 2000), Washington, D.C.

Walters, D.T., and G.L. Malzer. 1990. Nitrogen management and nitrification inhibitor effects on nitrogen-15 urea: II. nitrogen leaching and balance. Soil Science Society of America Journal 54:122-130.

Westfall, D.G., J.L. Havlin, G.W. Hergert, and W.R. Raun. 1996. Nitrogen management in dryland cropping systems. Journal of Production Agriculture 9:192-199.

Wood, C.W., D.W. Reeves, R.R. Duffield, and K.L. Edmisten. 1992a. Field chlorophyll measurements for evaluation of corn nitrogen status. Journal of Plant Nutrition 15:487-500.

Wood, C.W., P.W. Tracy, D.W. Reeves, and K.L. Edmisten. 1992b. Determination of cotton nitrogen status with a hand-held chlorophyll meter. Journal of Plant Nutrition 15:1435-1448.

Copyright © 2002 Soil and Water Conservation Society. All rights reserved.
Journal of Soil and Water Conservation 57(6):485-498 www.swcs.org