Management effects on nitrogen leaching and guidelines for a nitrogen leaching index in New York

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ABSTRACT: Management practices may affect the potential for nitrate leaching from agricultural systems. Two studies are discussed that used plot-size lysimeters on loamy sand and clay loam soil in Northern New York. One was conducted from 1991 to 1994 and involved sod plowing and the use of three rates of fertilizer on maize (*Zea mays* L.). The other study was conducted from 1997 to 2000 and quantified N-leaching losses under maize and orchardgrass (*Dactylis glomerata* L.) as affected by the timing of manure application. These studies showed that timing and rate of N fertilizer and manure additions, timing of green-manure incorporation, and soil type strongly influenced N-leaching losses. Losses from fall-applied N sources were high, especially on coarse-textured soils. Lower N losses in fine-textured soils were primarily the result of higher denitrification losses, rather than reduced percolation rates. It was concluded that the current N Leaching Index ignores important processes and requires a more dynamic approach that includes management factors. In the interim, we established a set of best management practices for N to reduce the potential for N leaching losses.

Keywords: Manure, N fertilizer, nitrate leaching, N Leaching Index, soil type, timing of application

Great improvements in water quality were made from regulation of point sources in the 1970s, and the majority of states now cite agriculture as the primary contributor to water-quality impairments. Besides causing nuisance aquatic vegetation, nutrient contamination of surface waters has broader ecological impacts. Hypoxia, or dissolved oxygen depletion, is a significant problem in many freshwater lakes in the Northeast and has reached alarming proportions in several of the nation's estuaries and the Gulf of Mexico (ERS 1997). The U.S. Geological Survey found 1% of community wells and 9% of rural, domestic wells contaminated with NO_3-N levels above the 10 mg L^{-1} Maximum Contaminant Level (MCL, Mueller et al. 1995). The proportion of contaminated wells was as much as 26% in areas with land used for intensive agriculture. In the Northeast, groundwater nitrate contamination typically appears in localized areas and can often be related to intensive agricultural or urban land uses on coarse-textured soils (Poe et al. 1998).

Leaching of N fertilizers. NO_3-N leaching under agricultural crops has been studied extensively, primarily through the use of suction lysimeters, monolith lysimeters, and subsurface drainage lines, with increasing amounts of spatial integration, respectively. Maize has been the most widely studied crop to determine the effects of agricultural management practices on nutrient losses (e.g., Baker and Johnson 1981, Kanwar et al. 1988, Kladivko et al. 1991, Randall and Iragavarapu 1995, Randall et al. 1997), generally showing higher nitrate levels in shallow groundwater with increasing fertilizer N levels. NO_3-N levels were often well above the 10 mg L^{-1} MCL under the optimum economic fertilizer levels as recommended by the state extension services.

A number of studies quantified NO_3-N leaching potential under different crops (e.g., Robbins and Carter 1980; Bergstrom 1987; Owens 1990; Randall et al. 1997). In general, they found the highest nitrate-N levels under maize, intermediate levels under less-fertilized annual crops (e.g., soybeans (*Glycine max* L.) and wheat (*Triticum aestivum* L.), and the lowest levels under perennial crops (e.g., alfalfa (*Medicago sativa* L.) and grasses). In fact, NO_3-N levels under the latter crops were generally well below the MCL. Besides changes in NO_3-N leaching losses, soil hydrologic patterns also varied among crops. Randall et al. (1997) found drainage from row crop systems to exceed that from perennial crops by 1.1 to 5.3 times, primarily as a result of different timing of crop-water uptake and rooting depths. Bergstrom (1987) similarly found higher drainage under barley (*Hordeum vulgare* L.) compared with fescue (*Festuca Rubra* L.) and alfalfa. Therefore, the process of NO_3-N leaching under different crops involves complex interactions between soil hydrology, climate, crop-water and nutrient uptake, and management practices. Use of perennial crops is often suggested as an alternative to row crops when NO_3-N leaching is of great concern (e.g., Schertz and Miller 1972, Meek et al. 1994, Randall et al. 1997, Yiridoe et al. 1997).

Leaching of manure N. Manure N includes a somewhat unstable component as urea in the liquid portion and a relatively stable organic N component in the feces, whose relative fractions may vary among manure types (Klausner et al. 1994). If manure is surface-applied and not incorporated, the urea converts fairly quickly to ammonium (NH_4) through hydrolysis and ammonia (NH_3) as the pH increases and the manure begins to dry. It may then be lost by NH_3 volatilization, depending on ambient conditions. If the manure is effectively incorporated, most of the urea is converted to ammonium and nitrate, thereby making it plant-available or subject to leaching or denitrification losses. The organic N component of manure mineralizes and becomes more gradually plant-available, typically represented by a decay series (representing the fraction of organic N that is available in each subsequent growing season, Magdoff 1978, Klausner et al. 1994). For New York conditions, it is assumed that 100% of the NH_4-N is available to maize if applied as a late-spring sidedress (although this is perhaps a slight overestimation, Paul and Beauchamp 1995), 65% if applied as spring plowdown (reduced if incorporation is delayed), and 0% otherwise (Klausner 1997).

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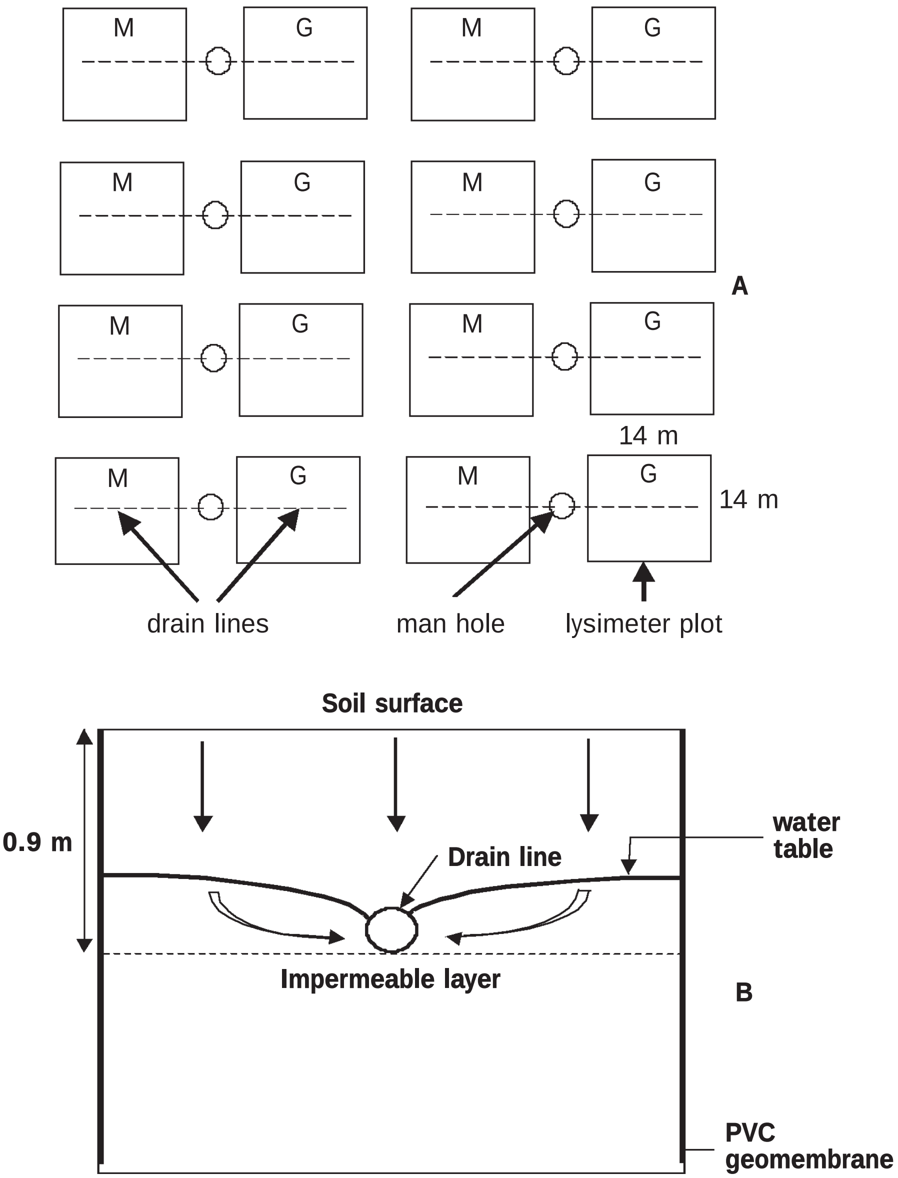
Figure 1

Plan view of 16 lysimeter plots (A), and cross-sectional view of one plot (B) on loamy sand site. The clay loam site is similar, but with 18x18 m plots and triple drain lines in each plot. Plots marked with M and G were under maize and grass, respectively, in the manure study.



The decay series for the organic N fraction is 0.35-0.12-0.05-0.02 (unless high in dry matter). However, it is recognized that the rate of N mineralization is strongly affected by variations in soil, climate, manure composition, and management factors (Barbarika et al. 1985, Douglas and Magdoff 1991, Klausner et al. 1994, Jackson and Smith 1997). Estimates for mineralization of the organic manure N fraction are lower for manure applied to poorly drained soil or left on the surface (compared with manure incorporated on well-drained soil). Magdoff (1978) estimated that manure N mineralization rates on a poorly drained Panton clay were about half those on a well-drained Calais loam, although the lower net mineralization rates may actually be the result of higher denitrification losses.

Besides estimates of plant availability, these studies also provide insight into potential environmental losses. Since urea-to-NH_4 and NH_4-to-NO_3 transformations may occur within a time period of several days (Kirchmann 1991), an incorporated fall manure application when soils are warm and crop uptake is nonexistent is likely to result in considerable nitrate leaching losses during the following winter and spring. Paul and Zebarth (1997) evaluated such leaching losses from fall-applied dairy cattle slurry on two soil types in coastal British Columbia (a poorly drained, coarse-textured soil and a well-drained, medium-textured soil, respectively) and determined them to average 40 kg ha^{-1} (35.7 lb ac^{-1}) above the no-manure treatment. Denitrification accounted for only 17% of the total nitrate losses and, therefore, was less significant than leaching. Smith and Chambers (1993) in England also determined that the application of high-N manures in the fall tends to result in excessive NO_3-N leaching losses and recommended against application during September to December. Manure applications also cease after Aug. 15 on the Dutch experimental farm, De Marke, which is managed to minimize NO_3-N leaching to groundwater (Aarts 1996).

Early spring manure application may result in NO_3-N release in advance of crop N uptake (Durieux et al. 1995) and may also result in leaching losses. Similarly, timing within seasons may have significant impacts on leaching potential. A late-fall application, when soil temperatures have decreased, may result in different N release patterns from early-fall application.

N-leaching losses from organic sources also strongly vary among cropping systems, although crops other than maize have not been extensively researched in the United States. Nonleguminous, cool-season, perennial hay crops have higher N demands (Klausner 1997), have longer active growth periods, and require different manure application schedules than maize. In addition, manure applied on grass is typically not incorporated, thereby reducing the availability of the urea-N fraction. Kaffka and Kanneganti (1996) measured greater crop response to manure application in a year with abundant rainfall than in a dry year with reported N recoveries as high as 60%.

Methods and Materials

Fertilizer study. During the period 1989 to 1997, we monitored nitrogen dynamics in plots on two sites that are <1 km (0.6 mi) apart at the Cornell University Willsboro Experimental Farm in northern New York. One site, with 16 plots of 14x14 m (45x45 ft,

Figure 2

Effect of fertilizer N rate on NO3-N concentrations in shallow groundwater under second- and third-year maize for a loamy sand and a clay loam soil.

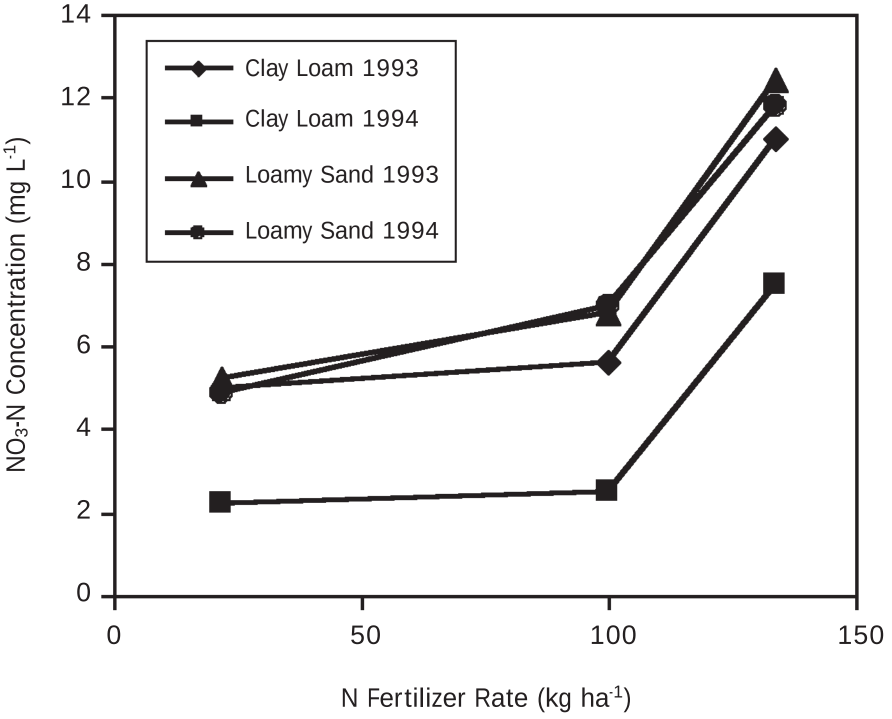


Figure 1A), was located on a Cosad loamy sand (sandy over clayey, mixed, mesic Aquic Udorthent), while the other with 16 plots of 18x18 m (60x60 ft) was built on a Kingsbury clay loam soil (fine, mixed, frigid, Aeric Ochraqualf). Each plot was surrounded by 0.8 mm (0.031 in) impermeable PVC geomembrane to a depth of 1.8 m (6 ft, Figure 1B), which made the plots hydrologically independent and allowed for leaching studies using replicated treatment allocations. Each plot was underlain by a very slowly permeable clay layer and had one drain line (loamy sand site) or three parallel drain lines (clay loam site) at a depth of 0.9 m (3 ft), allowing them to function as plot-size lysimeters. The central drain lines exited into a manhole, facilitating water sampling (Sogbedji et al. 2000)

From 1988 to 1991, a mixture of alfalfa (*Medicago sativa* L., cv. Oneida VR) and timothy (*Phleum pratense* L., cv. Climax) was grown on the clay loam site in a study to evaluate the effects of water management practices (Buscaglia et al. 1994) and the potential for preferential chemical movement (van Es et al. 1991). NO_3-N levels in drain outflow (representing shallow groundwater quality) remained between 1 and 2 mg L^{-1} (ppm) throughout this time period. In 1991, the loamy sand site was constructed into a pre-existing grass sod.

Sods were plowed in September 1991 for the clay loam soil and in April 1992 for the loamy sand. During 1992 to 1995, maize was grown on the plots under three N fertilizer levels, 22, 100, and 134 kg ha^{-1} (20, 90 and 120 lb ac^{-1}), with 22 kg ha^{-1} (20 lb ac^{-1}) applied as starter and the remainder as side-dress N. The 100 and 134 kg N ha^{-1} (90 and 120 lb ac^{-1}) treatments were replicated three times, while the 22 kg ha^{-1} (20 lb ac^{-1}) plot was replicated twice. The remaining eight plots at each site had obstructed drains and are not reported on here. Drain effluent rates were monitored continuously using 22.5° V-notch weirs combined with Telog Instruments high-sensitivity water-level depth pressure transducers and data loggers installed in the manholes (Sogbedji et al. 2000). Water samples were obtained when drain lines flowed at time intervals ranging from 2 hours to 4 days, depending on flow rate.

Results. Intensive monitoring of crop N uptake, soil N dynamics, and groundwater NO_3-N concentrations measured under the different N management systems provided insights into N-mass balances and the fate of N under these climate conditions (Sogbedji et al. 2000, 2001a, 2001b): Average NO_3-N levels remained near or under the 10 mg L^{-1} (ppm) MCL, even for the 134 kg ha^{-1} (120 lb ac^{-1}) rate, the highest Cornell University-recommended rate for maize on these soils (Figure 2). NO_3-N levels were generally similar for the 22 and 100 kg ha^{-1} (20 and 90 lb ac^{-1}) N rates, averaging 3.8 mg L^{-1} (ppm) for 1993 and 1994 under the clay loam, and 6.0 mg L^{-1} (ppm) under the loamy sand. However, NO_3-N levels significantly increased for the 134 kg N ha^{-1} (120 lb ac^{-1}) rate, averaging 9.3 and 12.1 mg L^{-1} (ppm) for the clay loam and loamy sand, respectively (Sogbedji et al. 2000). This suggests that with increasing fertilizer levels, N is efficiently taken up by the crop until a threshold value is reached (about 100 kg N ha^{-1} or 90 lb ac^{-1} in our case), after which uptake efficiency dramatically decreases. Residual soil nitrate levels and therefore nitrate leaching are then increased: 43% of the additional 34 kg ha^{-1} (30 lb ac^{-1}) N applied between the 100 and 134 kg ha^{-1} (90 and 120 lb ac^{-1}) rates was accounted for in groundwater under the loamy sand in the wetter year, 1994 (Sogbedji et al. 2000).

Shallow groundwater NO_3-N levels under the loamy sand were the highest during the fall (Sogbedji et al. 2000), and were strongly correlated with residual soil NO_3-N levels, as also measured for similar soils by Hack-ten Broeke and de Groot (1996). For the clay loam, groundwater NO_3-N levels were more evenly distributed during the year. This suggests rapid post-season leaching of residual soil NO_3-N in a coarse-textured soil.

Despite prominent differences in soil hydraulic properties, the two sites exhibited similar water-percolation rates during wet periods (early spring periods in all years and early summer of 1994, Sogbedji et al. 2000). During dry periods, differential soil retentivity resulted in varying water-percolation rates. Therefore, differential NO_3-N leaching losses for the two soil types during both wet and dry periods cannot be explained solely based on water-percolation, but are also strongly affected by N transformation dynamics (mineralization, nitrification, denitrification, etc.), and fundamental differences in solute flow processes (notably the extent of multidomain flow) among these soil types (Sogbedji et al. 2001a, 2001b). Indeed, the N-mass balance of data on soil N levels, crop uptake, fertilizer

Table 1. Rate coefficients for nitrification and denitrification from LEACHM calibrations (Sogbedji et al. 2001b).

	Rate coefficient	
Soil type	Nitrification	Denitrification
	d^{-1}	
Cosad Loamy Sand	0.391	0.004
Kingsbury Clay Loam	0.240	0.106

application, and leaching losses (Sogbedji et al. 2000) suggested that the clay loam site generally had much higher denitrification losses. Also, N-transformation rate coefficients were determined by calibrating the LEACHM model (Hutson and Wagenet 1992). This similarly showed higher denitrification rate coefficients for the clay loam soil (Table 1, Sogbedji et al. 2001b). This is also evidenced by the lower NO_3-N concentrations for the clay loam in the wetter year, 1994, compared with the drier 1993 (Figure 2).

The highest groundwater NO_3-N levels measured during this study occurred on the clay loam site after alfalfa plowdown in September 1991 (Sogbedji et al. 2000). Average flow-weighted NO_3-N levels increased from 2 mg L^{-1} (ppm) before plowdown to 10 mg L^{-1} (ppm) within weeks after plowing to 16 mg L^{-1} (ppm) during the next spring. This suggests that considerable NO_3-N leaching losses occur from organic sources, especially if the timing of application/plowdown occurs out of sync with crop uptake. The fact that leaching losses associated with this practice resulted in the highest NO_3-N leaching losses during the experiment merits attention, and it initially appears to contradict conclusions made by others (e.g., Schertz and Miller 1972, Smith et al. 1990, Meek et al. 1994, Randall et al. 1997) that alfalfa suppresses nitrate leaching. However, it appears that the organic N releases associated with crop transitions should be the primary concern. Indeed, researchers have found that alfalfa plowing often produces large amounts of NO_3-N through N mineralization of residues (Bruulsema and Christie 1987, Fox and Piekeliek 1988). Additionally, the timing of such N release relative to the establishment of a succeeding crop (Campbell et al. 1994, Francis et al. 1994), periods of water percolation, and the occurrence of N-transformation processes greatly influences the NO_3-N leaching potential.

The plot-size lysimeters provided good information on nutrient dynamics in this study. The results clearly suggested that more research emphasis needs to be placed on the management of organic N, which is the main source of N in the Northeastern United States and the focus of the second study.

Manure study. The plot-scale lysimeters were again employed from October 1997 to October 2000 to investigate nutrient leaching as affected by the timing of manure application, soil type (clay loam and loamy sand), and crop type (maize and orchardgrass, Figure 1). Liquid manure was applied starting in fall 1997 using a Nuhn Industries (Sebringville, Ontario) manure applicator. Four application periods were scheduled under the maize crop for each soil type: early fall (target date Oct. 1), late fall (Nov. 1), early spring (April 15), and a split early spring application and late spring sidedress (April 15 and June 15). Manure containing about 1.3 kg of organic N and 1.0 kg of ammonium-N per 1,000 L (10.9 and 8.4 lb per 1000 gal, respectively) was applied at a total annual rate of 93,800 L ha^{-1} (10,000 gal ac^{-1}) and was disk-incorporated within 2 hours of application. The split application treatment on maize received 46,900 L ha^{-1} (5,000 gal ac^{-1}) twice. Each manure treatment allocation was spatially balanced (van Es and van Es 1993) and replicated twice. Maize plots received an additional 30 kg ha^{-1} (27 lb ac^{-1}) fertilizer at planting and sidedress N based on the results of a Pre-Sidedress Nitrate Test (Magdoff 1991).

One set of three grass plots received 46,900 L ha^{-1} (5,000 gal ac^{-1}) of manure in early spring (April 15), and another set of three received that amount after the third cutting (Oct. 1). Plots not receiving manure at these times were fertilized with 71 kg N ha^{-1} (65 lb ac^{-1}) using ammonium nitrate. Both treatments also received such quantities of manure after the first and second cutting, for a total of 140,700 L ha^{-1} (15,000 gal ac^{-1}).

Drain-water samples were collected weekly during low-flow periods when drains were flowing and at least twice a week during periods after each manure application (for appropriate plots) and during high-flow periods. Maize was harvested for silage, while orchardgrass was harvested through three annual cuts.

Results. Preliminary results of this study show that crop type and timing of application strongly influence N leaching potential (Table 2). On both sites, nitrate concentrations under maize were significantly higher than those under orchardgrass, which were at very safe levels relative to the MCL. This may be attributed to higher ammonia volatilization from the lack of incorporation, as well as high N uptake potential and longer active growing period for the cool-season grass.

Flow-weighted mean concentrations in drain outflow under maize showed consistent effects of the timing of application (Table 2). Concentrations for early fall applications on the loamy sand soil were highest at 23.44 mg L^{-1} (ppm) NO_3-N indicating unacceptably high N leaching losses. A one-month delay resulted in a 4 mg L^{-1} (ppm) reduction in NO_3-N concentrations, presumably caused by lower mineralization and nitrification potential in cooler soil. NO_3-N concentrations under spring manure applications were approximately 12 mg L^{-1} (ppm), and significantly lower than fall applications. This demonstrates the benefits of N application closer to the time of crop uptake. No differences were observed between early spring

Table 2. Flow-weighted mean groundwater NO_3-N concentrations as affected by timing of application and soil type for the period fall 1997 to spring 2000.

Timing of Manure Application				
	Early fall	**Late fall**	**Early spring**	**Split application**
	mg L^{-1}			
Loamy sand				
Maize	23.44 a[†]	19.33 b	11.76 c	12.56 c
Grass	2.64 e		2.11 e	
Clay loam				
Maize	15.44 a	11.79 b	6.15 c	7.16 c
Grass	1.04 d		1.62 d	

[†] **Means for crop-timing combinations within each soil type followed by the same letter are not significantly different at _=0.05.**

application and the split early-late spring application. A similar pattern was observed for the clay loam soil where NO_3-N concentrations for each treatment under maize were 6 to 8 mg L^{-1} (ppm) lower than the respective treatment on the loamy sand, although still in some cases above the MCL. NO_3-N concentrations under orchardgrass on the clay loam soil were generally low with flow-weighted mean values under 3 mg L^{-1} (ppm).

Treatment effects on groundwater NO_3-N concentrations were generally consistent throughout the study period. However, temporal variations were considerable. Mean NO_3-N concentrations during the fall and winter of 1999 ranged from 25.41 to 57.66 mg L^{-1} (ppm) among treatments on the loamy sand site (data not shown), which is explained by a very dry 1999 growing season that resulted in high residual soil N levels subject to leaching during the following time period. This supports the notion that more attention needs to be paid to adjusting supplemental N applications based on weather conditions (Sogbedji et al. 2001c)

Results and Discussion

Management guidelines. The results of the fertilizer and the manure studies indicate that the environmental loss potential of N is strongly influenced by soil factors; weather; and amount, timing, and method of application. The associated processes are quite complex, but management guidelines can be established to help reduce N-leaching risk. The current Natural Resources Conservation Service (NRCS) N Leaching Index (based on precipitation and soil hydrologic grouping) separates soils of high and low leaching potential but ignores important processes such as management effects, preferential flow, and denitrification. A more dynamic approach is needed that allows for more accurate determination of N-leaching risk. This can be accomplished through the use of well-calibrated simulation models such as those used in this study (Sogbedji et al. 2001a, 2001b), and evaluating relative leaching potentials for various soil, climate, land-use, and management scenarios.

In anticipation of this, we have developed interim N management guidelines based on the current NRCS N Leaching Index that address the immediate concerns associated with certain N management practices, especially on soils with a high leaching potential. NRCS standard 590 categorizes N Leaching Index results as low (< 2), medium (2 to 10) and high (> 10). Producers are expected to implement best management practices if the Leaching Index score for a field is high (> 10). Producers are expected to consider these practices if the LI score for a field is medium (2 to 10). Based on the studies described above, these best management practices would be to:

- Avoid incorporating sod crops in the fall. Chemical sod killing may be carried out when the soil temperature at a 10 cm (4 in) depth approaches 8˚C (45˚F). Depending on location, this probably will not take place until early October.
- Minimize fall and/or winter manure application on good grass and/or legume sod fields that are to be rotated the next spring.
- Plant winter hardy cover crops whenever possible, especially when fall manure is applied (e.g., rye, winter wheat, or interseed ryegrass in summer).
- Apply manure in the fall on a growing crop with discretion. Judicious amounts of manure can be applied to or in conjunction with perennial crops or winter hardy cover crops. Applications should generally not exceed the greater of 55 kg ha^{-1} (50 lb ac^{-1}) of first-year available N or 50% of the expected N requirement of next year's crop.
- Note that frost incorporation/injection (van Es et al. 1998, van Es and Schindelbeck 2000) is acceptable when soil conditions are suitable, but winter applications should be made in accordance with the New York Phosphorus Index.
- Unless the New York Phosphorus Index identifies the need for P-based fertility management, base manure and fertilizer application rates on Cornell University guidelines for meeting crop N needs.

The last guideline is based on the results of our fertilizer study showing considerably higher N-leaching rates when N fertilizer in excess of the agronomic optimum is applied. Other best management practices associated with the current N Leaching Index are:

- For maize, pre-plant (other than starter fertilizer) and early post-plant broadcast applications of commercial nitrogen without the use of nitrification inhibitors are not recommended.
- Sidedress applications should be made after maize has at least four true leaves.
- If starter N must be broadcast (e.g., for small grains or new seedings of grass), apply fertilizer as close to expected planting date as possible (ideally within 3 days or less).
- For row and cereal crops, including maize, maintain starter fertilizer N rates below 55 kg ha^{-1} (50 lb ac^{-1}) actual N under normal conditions.
- Manure and fertilizer applications should be adjusted based on information provided in Nitrogen Recommendations for Field Crops in New York, Cornell University Department of Crop and Soil Sciences Extension Series E01-4 (Ketterings et al. 2001).
- Evaluate the need for sidedress N applications based on PSNT or other soil nitrate-nitrogen tests.
- Appropriate ammonia conservation is encouraged. Losses can either be reduced by immediately incorporating manure or eliminated by directly injecting manure as a sidedress application to growing crops.
- Manure N application on legumes is acceptable to satisfy agronomic requirements when legumes represent less than 50% of the stand. When legumes represent more than 50% of the stand, manure may be applied at a rate not exceeding 165 kg ha^{-1} (150 lb ac^{-1}) of available N.

Summary and Conclusions

This study confirmed that timing and rate of N management and soil type are important factors affecting N leaching, and high-risk management practices can be identified, as also suggested by work of Paul and Zebarth (1997), Smith and Chambers (1993), and Randall et al. (1997). The current NRCS Leaching Index does not address the dynamic nature of the N-leaching process. A new N Leaching Index needs to be developed, based on mechanistic simulation modeling results, that addresses interactions of soil type with land-use and management practices. In the interim, guidelines for N management in New York have been developed, based on the current NRCS N Leaching Index, that address the concerns related to practices with high nitrate leaching potential.

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