Nitrate concentration of subsurface drainage water from a corn field in southern New Brunswick

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Milburn, P. and Richards, J.E. 1994. Nitrate concentration of subsurface drainage water from a corn field in southern New Brunswick. Can. Agric. Eng. 36:069-078. The subsurface drainage discharge and associated nitrate-nitrogen (NO$_3$-N) concentration emanating from a continuously cropped corn field were monitored year round for four consecutive crop years, May 1989 to May 1993. Annual nitrogen (N) inputs were approximately 90 kg ha$^{-1}$, from a combination of manure and fertilizer N sources. The experimental site consisted of an on-farm field which was systematically subdrained by three equally sized (1 ha) plots, each with independent outlets. Over the four year duration of the study, maximum annual values of cumulative subsurface drainage discharge, NO$_3$-N lost in the drainage discharge, and flow-weighted NO$_3$-N concentration in the drainage discharge were 960 mm, 30.0 kg ha$^{-1}$, and 5.0 mg L$^{-1}$, respectively. The former two values were incurred the same crop year that maximum annual precipitation (1418 mm; 134% of normal) was received. The maximum mean seasonal flow-weighted NO$_3$-N concentration, which was computed for four distinct time periods of each crop year, was 13.4 mg L$^{-1}$ and occurred during the May to September period in 1992 when heavy rains followed shortly after fertilizer application. For the entire study period, approximately 85% of the total drainage discharge and 70% of the total NO$_3$-N leaching occurred outside the active (May to September) growing season.

Keywords: Nitrate leaching, subsurface drainage, corn production, groundwater quality, nonpoint source pollution

L’écoulement d’un système de drainage sub superficiel et la concentration de nitrate-azote (NO$_3$-N) émanant d’un champ de maïs en culture continue ont été enregistrés durant toute l’année pour une période de quatre années consécutives, de mai 1989 à mai 1993. Les apports annuels d’azote (N) ont été approximativement 90 kg ha$^{-1}$, et comprenaient de l’azote provenant d’engrais et de fumier. Le site expérimental consistait en un champ sur une ferme. Le champ a été séparé en trois parcelles égales (1 ha) et chaque parcelle possédait son propre tuyau de décharge. Durant les quatre années de l’étude, les valeurs annuelles moyennes maximum de l’écoulement cumulatif de drainage sub superficiel, des pertes de NO$_3$-N dans la décharge du drainage, et de la concentration (pondérée sur les flux) de NO$_3$-N dans la décharge du drainage ont été respectivement 960 mm, 30.0 kg ha$^{-1}$, et 5.0 mg L$^{-1}$. Les deux premières valeurs ont été obtenues durant l’année au cours de laquelle la précipitation annuelle maximum a été enregistrée (1418 mm; 134% de la normale). La valeur maximum de concentration moyenne saisonnière de NO$_3$-N, qui a été calculée pour quatre périodes distinctes de chaque année de croissance, a été 13.4 mg L$^{-1}$ et est survenue durant la période de mai à septembre 1992, lorsque des pluies intenses ont suivi de près l’application d’engrais. Pour la durée entière de l’étude, environ 85% de l’écoulement de drainage sub superficiel et 70% de la quantité totale de NO$_3$-N émanant du champ se sont produits en-dehors de la saison active de croissance (de mai à septembre).

INTRODUCTION

The effect of agriculture on water quality is currently a high profile issue. More specifically, the widespread agricultural practice of nitrogen (N) application, either from fertilizer or animal sources, to enhance soil fertility has been targeted as a potential cause of nonpoint source (NPS) nitrate-nitrogen (NO$_3$-N) contamination (Follet et al. 1991; Follet 1989; Magette et al. 1989). Indeed, Fletcher (1991) commented that NO$_3$-N leaching from agricultural lands in the USA is considered as one of the most significant NPS of groundwater contamination.

Due to rising concerns over NPS groundwater contamination, Strebel et al. (1989) suggested that quantification of NO$_3$-N leaching should become a more common aspect of agronomic field experiments. Milburn and MacLeod (1991) and Hallberg et al. (1986) reviewed several studies where subsurface drainage discharge was employed to estimate NO$_3$-N and pesticide leaching from below the crop root zone. Because it is often released to surface ditches or streams, subsurface drainage discharge can pose a threat to surface water quality; however, subsurface drainage discharges can also indicate the chemical composition of natural drainage losses to groundwater under the influence of agricultural practices (Kladivko et al. 1991). Indeed, Hallberg et al. (1986) reported that the hydrologic responses and mass losses observed in subsurface drainage studies were directly analogous to results from larger scale groundwater studies. Subsurface drainage studies can therefore be helpful in assessing the impacts of agricultural practices on both surface and groundwater quality.

In Canada, research into the water quality consequences of agricultural practices is just beginning (Milburn et al. 1992). In Atlantic Canada, where 1.2 million people are dependent on groundwater sources for water supplies, published information on NO$_3$-N leaching associated with crop production systems common to the region is available only for potatoes. In an on-farm study in New Brunswick (NB), Milburn et al. (1990) found that the flow-weighted average NO$_3$-N concentration of systematic subsurface drainage discharge for the period May to December from fields currently cropped to potatoes was consistently greater than 10 mg L$^{-1}$. For fields...
with a history of potato production, these concentrations remained above 10 mg·L⁻¹ during the next non-potato year when fertilizer N inputs were substantially reduced, suggesting that there was considerable residual N left in the soil after the potato crop was harvested. In another NB study, Richards et al. (1990) determined that the average NO₃-N concentration in water from private groundwater wells was greater in areas of intensive potato production than in rural, non-agricultural areas.

Corn is another high input crop in Atlantic Canada, with a recommended N application rate of 90 to 130 kg·ha⁻¹ (Clare et al. 1985). Most of the corn is used to produce silage for dairy cows. Approximately 5000 ha of corn are produced annually for silage in Atlantic Canada (Statistics Canada 1986).

In other areas of North America, corn production practices have been linked with nitrogen build-up in the soil and subsequent NO₃-N leaching to groundwater (Angle et al. 1993; Magdoff 1978, 1991; Schepers et al. 1991; Jokela and Randall 1989; Legg et al. 1989). The objective of this study, therefore, was to determine annual nitrate leaching losses associated with recommended field-scale corn production practices in southern NB. A precise accounting of nitrogen dynamics (e.g. mineralized soil N, denitrification, immobilization, crop uptake) was not attempted. Instead, emphasis was placed on obtaining an initial estimate of field-scale NO₃-N leaching as an indicator of the relative potential for NO₃-N groundwater contamination resulting from corn production. This was achieved through year-round measurement of subsurface drainage flow rate and concomitant NO₃-N concentration from a commercial corn field.

**MATERIALS AND METHODS**

The study was conducted on a commercial dairy farm where systematic subsurface drainage outflows and concomitant nitrate N concentrations were measured year round for four years of continuous corn production, May 1989 to May 1993. Nitrate-nitrogen leaching was expressed as the annual NO₃-N flux in the subsurface drainage discharge and as the flow-weighted mean annual NO₃-N concentration of the subsurface drainage discharge. The latter can be used directly as a contaminant source input in groundwater quality models.

**Site and soil conditions**

The experimental site was an 8-ha field near the town of Sussex, NB (Fig. 1). The topography was undulating, with slopes from two to four percent. The soil was classified as an imperfectly drained Peticotid soil with gravelly clay loam composition throughout the main or collector line and not in the experimental area occupied by the experimental site. Soil bulk densities below 0.4 m depth and surface soil organic carbon (O.C.) content of the Peticotid soil and other locations throughout the survey area were reported as approximately 1.8 Mg·m⁻³ and 3.2%, respectively. Sixteen soil samples (0-0.15 m depth) were collected at random locations throughout the experimental area prior to drainage system installation in 1988. Samples were bulked and analyzed for O.C. using dry combustion followed by CO₂ detection by infrared absorption (Tieszen and Moir 1993). The organic carbon content was determined to be 3.6%.

Loam to clay loam lodgement till soils with compacted subsoils less than 0.5 m from the soil surface are common in NB, encompassing 1.8 million hectares (Agriculture Canada 1989).

The meteorological station nearest the experimental site for which 30-year climatic normals were available was the Environment Canada station located at Sussex, 25 km to the west (Fig. 1). Precipitation data from Sussex were used as an estimate of rainfall at the experimental site (Environment Canada 1982).

**Drainage system**

A schematic of the subdrainage system at the experimental site is shown in Fig. 2. Four drainage plots of identical area (1.1 ha) were separated by a random subdrainage configuration in the centre. Each of the drainage plots had a separate main or collector line that lead to a common data collection shelter where flow rates were measured and water quality samples were collected. Thus, it was possible to record variation in drainage discharge and drainage water quality within a single commercial corn field. Only plots A, C, and D were included in the study because plot B had extensive inclusions of shallow organic soil underlain by heavy clay (not indicated in the soil survey) that resulted in marginal drainage and soil conditions not conducive to crop growth.

Drain spacing, length, depth, and number of drain laterals were constant among plots at 12 m, 65 m, 0.8 m, and 13, respectively. Drain depth and spacing were similar to other on-farm drainage systems commonly employed in the region. Buffer drains connected to non-monitored outlets were installed around each plot to minimize border hydraulic effects between plots and between plots and adjacent undrained land. All of the fields in the immediate vicinity of the experi-
mental site were imperfectly to poorly drained and were not subdrained. Surface runoff from the north and northeast was not prevented from entering the experimental site. The drainage system was not extended north to the highway, coincident with the extent of the corn field (Fig. 2), due to financial constraints at the time of installation.

Field data collection

Methods of drainage discharge flow measurement, sample collection and handling, calculation of drainage area, and calculation of flow-weighted NO3-N concentrations were similar to those described by Milburn et al. (1990). Prefabricated 25 mm Parshall flumes equipped with Omnidata WL1 Datapod stage recorders (Omnidata International, Inc., Logan, UT) were used to record hourly drain discharge rates. ISCO Model 2900 wastewater samplers (ISCO, Lincoln, NE) with a capacity of 24 one-litre plastic bottles were used to automatically collect drainage water samples. Water samples were stored in sealed plastic containers and refrigerated until analysis. Nitrate-nitrogen concentrations were determined colorimetrically following hydrazine reduction (Technicon 1986).

Two drainage water sampling protocols were employed during the study. Discrete one-litre samples were collected every 8 h for the first two crop years. In an effort to obtain a more representative sample, one litre composite samples (250 mL every 2 h) were collected every 8 h for the final two crop years. In the former case, NO3-N flux from each drainage plot was calculated as described by Milburn et al. (1990).

Hourly sample concentrations were multiplied by average hourly flow volumes and summed for the period of interest. Hourly concentration data were derived by assuming a linear relation between measured (8 h) concentration points. In those few instances where equipment malfunction interrupted sampling, a linear interpolation between measured concentration points was employed. For the period of composite sampling, NO3-N fluxes were calculated by multiplying the concentration of the composite sample by the flow volume of the preceding 8-h period and summing for the period of interest. Calculation of flow-weighted concentrations was similar in both cases. The calculated NO3-N loss for the period of interest was divided by the corresponding total flow for that period.

To assess the seasonal nature of NO3-N leaching at the experimental site and to gain possible insight into the leaching process at other sites in southern NB with similar soil and climate conditions, we arbitrarily divided the crop year into four distinct periods. The cumulative drainage, associated NO3-N flux, and flow-weighted mean NO3-N concentration of the drainage effluent were calculated for each. These periods were: 1) the growing season, including planting, from May 15 to September 15; 2) fall, from September 16 to December 15; 3) winter, from December 16 to March 15; 4) and spring melt, from March 16 to May 14, continuing to just prior to planting.

Cropping program

All field operations in this experiment were performed by the farmer. Due to its naturally poor drainage condition, the experimental site was only passively cropped to single cut hay prior to installation of the drainage system (Fig. 2) in August, 1988. Prior to fall moldboard plowing in 1988, NO3-N concentrations of random samples of the drainage discharge were approximately 1 mg·L⁻¹. In May 1989, corn was planted and the site remained in corn production up to and including the 1992 crop year. The source of applied N for all corn crops was a combination of fertilizer N and liquid dairy manure (Table I). Fertilizer was banded at planting. Liquid manure was surface applied (without immediate soil incorporation) in the spring and worked into the soil prior to planting. Liquid manure was also fall applied in 1988 and 1991. Nitrogen credits for the liquid manure were adjusted for leaching and volatilization losses in accordance with the Advisory Committee on Soil Fertility (1981). For example, N credits for fall and spring applied liquid cattle manure, without immediate soil incorporation, were 0.5 and 1.0 kg N·m⁻², respectively. A summary of fertility and tillage inputs is provided in Table I. Herbicides atrazine (Aatrex; 480 g·L⁻¹ active) and dicamba (Banvel 480; 480 g·L⁻¹ active) were applied according to accepted practices.

RESULTS AND DISCUSSION

Annual totals

The annual crop year precipitation (May 15 to May 14) at Sussex and corresponding annual cumulative drainage discharge, NO3-N leached in the drainage discharge and average annual flow-weighted NO3-N concentration of the drainage discharge (NO3-Nf; subscript f denotes the flow weighted
Table I. Crop management at experimental site

<table>
<thead>
<tr>
<th>Year</th>
<th>Corn variety</th>
<th>Planting date</th>
<th>Fertilizer N (kg N ha⁻¹)</th>
<th>Manure</th>
<th>Harvested as</th>
<th>Harvest date</th>
<th>Primary tillage</th>
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<td></td>
</tr>
<tr>
<td>1989</td>
<td>Euros LG3</td>
<td>May 30</td>
<td>45</td>
<td>35</td>
<td>whole plant silage</td>
<td>Sept. 15-30</td>
<td>moldboard plow; spring and previous fall</td>
</tr>
<tr>
<td></td>
<td>(Hyland)</td>
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<tr>
<td>1990</td>
<td>Euros LG3</td>
<td>June 5</td>
<td>35</td>
<td>70</td>
<td>high moisture ear corn</td>
<td>Nov. 1-15</td>
<td>chisel plow; spring</td>
</tr>
<tr>
<td></td>
<td>(Hyland)</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>1991</td>
<td>3195</td>
<td>May 26</td>
<td>20</td>
<td>70</td>
<td>high moisture ear corn</td>
<td>Nov. 1-15</td>
<td>moldboard plow; previous fall</td>
</tr>
<tr>
<td></td>
<td>(Hyland)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1992</td>
<td>3195</td>
<td>May 23</td>
<td>20</td>
<td>70</td>
<td>high moisture ear corn</td>
<td>Nov. 1-15</td>
<td>moldboard plow; previous fall</td>
</tr>
</tbody>
</table>

¹Row spacing 760 mm; planting populations were 65,000 seeds ha⁻¹ in 1989 and 1990, and 72,000 seeds ha⁻¹ in 1991 and 1992.
²Fertilizer N sources were 250 kg ha⁻¹ diammonium phosphate (DAP) in 1989, 200 kg ha⁻¹ DAP in 1990, and 200 kg ha⁻¹ (N as monoammonium phosphate) in 1991 and 1992; all were banded at planting. Liquid dairy slurry was applied at a rate of 70 m³ ha⁻¹ throughout the study: fall applied in 1988 and spring applied without immediate incorporation in 1990, 1991, and 1992.
Manure N credits are in accordance with the Advisory Committee on Soil Fertility (1981).


average concentration) for each plot are summarized in Fig. 3. Mean annual values are also indicated. Annual precipitation was 102, 132, 117, and 101% of normal for crop years 1989-90 through 1992-93, respectively (Fig. 3a). Cumulative drainage discharge and annual NO₃-N leached was greatest for 1990-91, the crop year with the greatest annual precipitation (Fig. 3b, 3c). The greatest mean NO₃-Nf was 5.0 mg L⁻¹ in 1992-93, with a maximum individual plot value of 6.4 mg L⁻¹ (Fig. 3d).

The relative magnitude of annual drainage discharge and annual NO₃-N leached annually among plots remained constant throughout the experiment, that is, plot D>C>A for annual drainage discharge and D>A>C for NO₃-N leached annually. Possible reasons for the systematic difference in annual drainage discharge are discussed in the following section. In the case of NO₃-N leaching, it is not readily apparent why plot C consistently yielded less NO₃-N in the drainage water than plot A, even in the presence of more total cumulative discharge than plot A. Possible explanations include: 1) less net mineralization of N from soil organic matter in plot C; 2) more plant uptake of N in plot C; 3) greater denitrification or other gaseous N losses from plot C; 4) less N systematically applied to plot C due to ineffective fertilizer or manure spreading; 5) considerable preferential flow in plot C, resulting in cumulative drainage but incomplete leaching action through the soil profile. From the data collected, we cannot define precisely the relative contribution of these factors that resulted in less NO₃-N leaching from plot C. However, it is likely that conditions similar to those of plots C are present to some degree in many of the corn fields of southern NB and that the range of leaching losses measured in this experiment are indicative of those occurring at other on-farm sites in southern NB with similar soils and where similar production practices are employed.

Drainage discharges
Plot A consistently exhibited lower annual discharge than the other two plots (Fig. 3b). Some of the variation in discharge among plots could be due to variations in soil properties such as hydraulic conductivity and infiltration rate; however, upward or lateral seepage was observed (and recorded as discharge) in plots C and D, as evidenced by prolonged outflow in these plots, in the absence of rainfall, several days to weeks after flow had ceased in plot A. Seepage flow rates were consistently observed to be greater and persist longer in plot D. In addition to the seepage component, we speculate that some of the differences in total flows among plots were caused by surface runoff inputs from adjacent land, which affected plots C and D more than plot A (Fig. 2). Although quantification of these effects is not possible from the data collected, the annual plot drainage discharges appear reasonable relative to one another. They also highlight the fact that in NB, with its rolling topography and abundance of shallow and imperfectly to poorly drained soils (Milburn et al. 1989), there can be substantial contributions to subsurface drainage discharge from: 1) runoff from adjacent, undrained land, and; 2) upward or lateral seepage. Because the contributions to drainage discharge of seepage and runoff from adjacent land were least for plot A, we postulate that drainage discharges from plot A are the most representative estimates of leaching volumes in southern NB in the absence of these factors. Over the course of the study, cumulative drainage discharge from
1990-91 1991-92

b) PRECIPITATION
% OF NORMAL

Fig. 3, Crop year (May 15 to May 14) precipitation, drainage discharge, and NO3-N leaching loss at the experimental site: a) precipitation estimate, from meteorological station at Sussex; b) cumulative subsurface drainage discharge; c) cumulative nitrate N removed in the drainage discharge; d) flow-weighted mean annual NO3-N concentration of the drainage discharge.

plot A ranged from 38 to 57% of annual precipitation (400 to 700 mm). Given that average annual potential evapotranspiration (PET) in southern NB is approximately 550 mm (Dzikowski et al. 1984) and that annual precipitation during our study ranged from approximately 1100 to 1350 mm, these values seem reasonable. They are similar to maximum discharges reported in other drainage-water quality studies conducted in temperate areas (Table II).

Figure 4 shows the seasonal distribution of drainage discharges over the duration of the experiment, together with precipitation expressed as percent of the 30 year normal for the growing and fall seasons (Fig. 4a, 4b). There was considerable variation in the quantity of seasonal discharge, as would be expected with varying annual precipitation patterns. However, the magnitude of seasonal plot discharges relative to each other was similar to the annual trend of Fig. 3b, that is, D>C>A in all but three cases.

**Seasonal drainage and NO3-N leaching**

Mean values of seasonal plot drainage discharge and NO3-N leaching as a percent of annual plot drainage discharge and NO3-N leaching are presented in Fig. 5. (Average deviation from mean percentage values was 2% and 3% for drainage discharge and NO3-N leaching, respectively; data not shown.) From Fig. 5 it is evident that, for the four crop years of the study, a maximum of 20% of the annual drainage discharge and 55% of the annual nitrate leaching occurred during the growing season. Approximately one half or more of the annual NO3-N leaching occurred during the dormant part of the crop year. Considering cumulative drainage and NO3-N leaching for the entire duration of the study (mean values of 2497 mm and 88 kg·ha⁻¹), approximately 85% of the drainage and 70% of the NO3-N leaching occurred outside the May to September growing season. Other investigators have cited similar trends (Baker et al. 1975; Jones and Zwerman 1972; Patni et al. 1984), but this is the first quantification of year round leaching phenomena under conditions common to Atlantic Canada.

To illustrate the changing NO3-N concentration of the drainage discharge with season, the flow-weighted seasonal NO3-N concentration of the subdrainage discharge from each plot is graphed with time in Fig. 6. A similar trend among plots is evident. The peak in December 1989 indicates that there was sufficient NO3-N remaining in the soil that particular fall, from inorganic or organic sources, to cause an increased flow-weighted average NO3-N concentration. The peaks in September 1990 and 1992 indicate that during the growing seasons in those particular years, precipitation causing drainage probably occurred at a time when NO3-N was readily available, such as shortly after fertilizer application, thus resulting in considerable NO3-N leaching and an increase in the flow weighted NO3-N concentration. The magnitude of the increase is a function of the volume of drainage, the extent of N mineralization, and the timing of the rainfall event in relation to the time of fertilizer application. An example of one of the leaching events that lead to the substantial increase in NO3-N concentration during the 1992 growing season is shown in Fig. 7. This was the first drainage event since fertilizer application on June 2. Because there had been little time for N uptake by the corn crop when the
Table II. Maximum annual cumulative drainage discharge from selected studies

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Location</th>
<th>Soil texture</th>
<th>Cumulative drainage (mm)</th>
<th>% Annual precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baker et al. 1975</td>
<td>Iowa</td>
<td>silt loam</td>
<td>374</td>
<td>50</td>
</tr>
<tr>
<td>Bergstrom and Brink 1986</td>
<td>Sweden (central)</td>
<td>clay</td>
<td>365</td>
<td>57</td>
</tr>
<tr>
<td>Gustafson 1987</td>
<td>Sweden (south)</td>
<td>clay</td>
<td>520</td>
<td>52</td>
</tr>
<tr>
<td>Jackson et al. 1973</td>
<td>Georgia</td>
<td>loamy sand</td>
<td>483</td>
<td>41</td>
</tr>
<tr>
<td>Jones and Zwerman 1972</td>
<td>New York</td>
<td>loam</td>
<td>470</td>
<td>50</td>
</tr>
<tr>
<td>Kladivko et al. 1991</td>
<td>Indiana</td>
<td>silt loam</td>
<td>274</td>
<td>23</td>
</tr>
<tr>
<td>Logan et al. 1980</td>
<td>Minnesota</td>
<td>clay loam</td>
<td>410</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Ohio</td>
<td>clay</td>
<td>228</td>
<td>34</td>
</tr>
<tr>
<td>Madramootoo 1990†</td>
<td>Quebec</td>
<td>clay</td>
<td>289</td>
<td>33</td>
</tr>
<tr>
<td>Madramootoo et al. 1992‡</td>
<td>Quebec</td>
<td>sandy loam</td>
<td>466</td>
<td>63</td>
</tr>
<tr>
<td>Patni et al. 1984</td>
<td>Ottawa, ON</td>
<td>clay loam</td>
<td>-</td>
<td>44</td>
</tr>
</tbody>
</table>

† Drain spacings 10 m or more.
‡ 23y Drainmod simulation. April 15 to November 30.
§ April to November only; field data.

Fig. 4. Cumulative drainage discharge by season: a) growing season; b) fall; c) winter; d) spring. [Percentage normal seasonal precipitation estimated from monthly weather records at Sussex and monthly 30 y normals provided by Environment Canada(1981)].
drainage event occurred, N was readily available for leaching and NO₃-N concentrations up to 25 mg•L⁻¹ were measured. In a potato study, Milburn et al. (1990) presented similar graphs for NO₃-N leaching that occurred early in the crop year when NO₃-N was in abundant supply. Nitrate-N concentrations changed abruptly, coincided with peak flow, and decreased as drainage discharge decreased, as in Fig. 7. They also showed that later in the same crop year, when less NO₃-N was available for leaching, NO₃-N concentrations in drainage discharge decreased with peak flow and increased as drainage discharge decreased. Both of these processes were discussed and linked to the effect of preferential flow on NO₃-N leaching.

Other studies
A summary of selected NO₃-N leaching studies associated with corn production in various temperate to humid regions of North America is provided in Table III. Annual leaching losses range from 3 to 61 kg NO₃-N•ha⁻¹; mean annual NO₃-N concentrations of drainage discharge or groundwater range from 4 to 37 mg•L⁻¹. Our results are within these ranges, with our annual NO₃-N concentrations low and our annual NO₃-N leaching losses moderate (20-30 kg N•ha⁻¹). It is interesting to note that, given the mean concentrations reported in Table III, approximately 200 mm drainage discharge or less is required to produce the reported annual N leaching loss in most cases (leaching loss = mean concentration x drainage discharge, with appropriate units). Only the studies of Jackson et al. (1973) and Miller (1979); (sand at 200 kg N•ha⁻¹) showed annual drainage discharges in excess of 300 mm, similar to our experiment.

Further considerations
Consider that, given a mean annual drainage discharge through the soil profile of approximately 520 mm and a mean annual NO₃-N of that drainage discharge of 4 mg N•L⁻¹, as in plot A for our study, another 31 kg N•ha⁻¹ could be leached before the mean annual NO₃-N of the drainage discharge would equal the drinking water guideline of 10 mg•L⁻¹ (CCREM 1987). Baker and Johnson (1981) suggested that fertilizer N in excess of crop needs was almost entirely subject to loss by leaching; conversely, applied N
Table III. Nitrate-nitrogen leaching with corn: results from selected studies

<table>
<thead>
<tr>
<th>Investigator; location</th>
<th>Study duration (y)</th>
<th>Previous land use</th>
<th>Soil type</th>
<th>Study type</th>
<th>Annual N input (kg·ha⁻¹)</th>
<th>Average annual NO₃-N conc. (mg·L⁻¹)</th>
<th>Average annual NO₃-N loss (kg·ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gast et al. 1978; Minnesota</td>
<td>3</td>
<td>no N inputs</td>
<td>clay loam</td>
<td>tile</td>
<td>112</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(28 m)</td>
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<td>43</td>
<td>59</td>
</tr>
<tr>
<td>Gold and Loudon 1989;</td>
<td>2</td>
<td>corn</td>
<td>loam</td>
<td>tile</td>
<td>200</td>
<td>12**</td>
<td>27**</td>
</tr>
<tr>
<td>Michigan</td>
<td></td>
<td>(18 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hubbard et al. 1986;</td>
<td>1</td>
<td>NR</td>
<td>sand</td>
<td>shallow</td>
<td>87</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>Georgia</td>
<td>(not reported)</td>
<td></td>
<td></td>
<td>groundwater</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(2.1 m depth)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jackson et al. 1973;</td>
<td>3</td>
<td>NR</td>
<td>loamy sand</td>
<td>tile</td>
<td>200</td>
<td>7‡</td>
<td>34</td>
</tr>
<tr>
<td>Georgia</td>
<td>(single line)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>22</td>
</tr>
<tr>
<td>Kladivko et al. 1991;</td>
<td>3</td>
<td>corn</td>
<td>silt loam</td>
<td>tile</td>
<td>285</td>
<td>21‡</td>
<td>44</td>
</tr>
<tr>
<td>Indianna</td>
<td>(10 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>33</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Miller 1979; Ontario</td>
<td>2</td>
<td>corn</td>
<td>sand</td>
<td>tile</td>
<td>150</td>
<td>6.3§</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>(3 sites)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>spacing NR</td>
<td></td>
<td>clay</td>
<td>sand</td>
<td>110</td>
<td>4.7</td>
<td>12</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>4</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11.3</td>
<td>61</td>
</tr>
<tr>
<td>Prunty and Montgomery 1991;</td>
<td>4</td>
<td>-</td>
<td>loamy fine</td>
<td>lysimeter</td>
<td>95</td>
<td>11††</td>
<td>24*</td>
</tr>
<tr>
<td>North Dakota</td>
<td></td>
<td>(2.3 m depth)</td>
<td>sand</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

† Arithmetic mean(s), unless otherwise stated.
‡ Flow-weighted mean(s).
§ Data from March to November only.
* Overall mean across all treatments and years.
** Two-year mean and NO₃-N loss, including 1 year of peas at 31 kg·ha⁻¹ applied N.

That was less than the optimum required by plants was utilized by plants rather effectively and was not likely to be lost to leaching. Crop development at our study site was regularly observed by an agronomist of the NB Department of Agriculture; also, yield was measured in 1990 as part of a 3-year NB Department of Agriculture survey of on-farm corn yields in the Sussex region. From these indicators, yields at our study site were estimated at the regional average of 5 and 10 t·ha⁻¹ dry matter for high moisture ear corn and whole plant corn silage, respectively (Personal Communication: Walter Brown, Crop Specialist, NB Department of Agriculture, Sussex, NB). Therefore, since some yield increase could reasonably be expected, it is unlikely that a modest increase in applied N would substantially increase NO₃-N leaching.

**SUMMARY AND CONCLUSIONS**

To estimate NO₃-N leaching losses from farm-scale corn production practices in southern NB, we monitored the quantity and quality of subsurface drainage discharges from an on-farm field year round for four consecutive corn crops. Site conditions of rolling topography and shallow topsoil with dense, compact subsoil are typical of the agricultural land of southern NB. All inputs to the corn crop were controlled by the farmer. A combination of fertilizer N and liquid dairy...
slurry were applied annually to produce a recommended N rate of approximately 90 kg ha⁻¹. Nitrogen credits for the slurry were in accordance with current guidelines. Because of the on-farm, farmer-controlled cropping regime employed, this study incorporated most of the uncertainties characteristic of day-to-day crop production. These include, but are not limited to variations in soil physical properties and natural soil fertility, variations in nutrient content of the liquid manure and its distribution in the field, the effects of uncontrolled runoff from adjacent undrained land, the effects of traffic pattern on infiltration and runoff, and the relative efficacy of pesticide treatment throughout the field. Results are therefore both "field effective" and site specific.

We observed that:

1) Mean annual flow weighted NO₃-N concentrations of the drainage discharge ranged from 2 to 5 mg L⁻¹, considerably below the drinking water standard of 10 mg L⁻¹;
2) mean annual NO₃-N losses ranged from 10 to 30 kg ha⁻¹;
3) mean annual drainage discharge volumes were approximately equal to maximum annual volumes reported by other investigators;
4) approximately 85% of the total drainage discharge volume that occurred during the four-year study was accumulated outside the active (May to September) growing season.

We conclude that the flow-weighted annual NO₃-N concentration in drainage discharge from recommended corn production systems at 90 kg ha⁻¹ annual applied N on similar sites and soils in NB would not exceed 10 mg L⁻¹. Future research that incorporates controlled N inputs and a broader range of N dynamics than leaching only (e.g., mineralization, denitrification) would greatly enhance our total understanding of N processes in NB soils.

ACKNOWLEDGEMENT

The cooperation of dairy farmer, Mr. Joerg Van Waldow, Corn Hill, NB is gratefully acknowledged. Appreciation is also extended to the Atlantic Land Improvement Contractors Association (ALICA) and staff of the Soil and Water Section, Land Resources Branch, NB Department of Agriculture for assistance in field layout and installation of the drainage plots. The comments and insights of Mr. Walter Brown, Crop Specialist, NB Department of Agriculture, Sussex, NB were also most helpful.

REFERENCES


Clare, S., J. Goit and D. Mellish (eds.). 1985. Field crop guide for the Atlantic Provinces. Publication No. 100, Atlantic Provinces Agriculture Services Coordinating Committee. New Brunswick Department of Agriculture, Fredericton, NB.


