Simulating Nitrogen Dynamics Under Water Table Management Systems with DRAINMOD-N

C. A. Madramootoo, J. W. Kaluli, G. T. Dodds

Abstract. *There is increasing interest in water table management to control nitrate leaching in eastern Canada. However, little is known about the impacts of this practice in the region. DRAINMOD-N, a recently developed drainage water quality model, offers the potential to evaluate nitrate leaching. The model was validated by comparing simulated results with measurements of water table depth, drain flow, cumulative nitrate leaching, and cumulative denitrification, from conventional drainage and subirrigation field plots planted to corn. Replicated plots of 15 m × 75 m were either under conventional free drainage or subirrigation at a weir setting of 0.5 m below the soil surface. DRAINMOD-N predicted water table depth to within a range of ±160 to 210 mm, drain flow to within ±2 mm/d and nitrate leaching to within ±8 kg N/ha. DRAINMOD-N models denitrification using first order kinetics. This did not accurately describe field measurements of cumulative denitrification, as by day of year 270 cumulative denitrification was underestimated by 64 to 83%. Therefore, the model was modified by replacing the original denitrification function with the Michaelis-Menten relationship, which simulates denitrification as a first order process when nitrate is limiting and as a zero order process for non-limiting nitrate. This modification had little effect (< 2%) on the modified model's prediction of nitrate leaching. For cumulative denitrification, however, the prediction error with the modified model was of 23 to 60% less than with DRAINMOD-N.*

Keywords. *Nitrate, Water quality, Leaching, Computer simulation, Water table management, Drainage.*

According to Duttweiler and Nicholson (1983), worldwide annual agricultural runoff contributed an estimated 4.65 million tons of nitrogen (N) to off-farm aquatic ecosystems, primarily in the form of nitrate (NO_3^-). Along with phosphate, nitrogen is often limiting in aquatic plant ecosystems, so that its introduction into such ecosystems often leads to excessive plant growth. Bacterial decomposition of the resultant biomass eventually contributes to reducing oxygen levels in the water. When dissolved oxygen levels drop below 4 mg/L, most fish species can no longer survive. Another effect of increasingly anaerobic conditions is the shift in the nitrification-denitrification balance towards the production of ammonia. As little as 0.02 mg/L of ammonia can be lethal to aquatic flora and fauna (Cooper, 1993). The main source of NO_3^- reaching these ecosystems is from fertilizers used in modern agriculture (Cooper, 1993). In the United States, about 25% of lakes house ecosystems that are impaired or partially impaired, and 20% that are threatened by nutrients and sediments (USEPA, 1989). Close to 60% of impaired lake hectares, 55% of impaired stream hectares, and 20% of impaired estuarine hectares can be attributed to nutrients and sediments from agricultural sources (Wells, 1992).

Nitrate is also the most ubiquitous pollutant in the world's aquifers, with levels that continue to increase (Spalding and Exner, 1993). In human blood, NO_3^- is reduced to nitrite (NO_2^-), which in turn converts erythrocyte hemoglobin to methemoglobin. This reduces the capacity of blood to carry oxygen and causes a blood disorder known as methemoglobinaemia or blue baby syndrome (Bruning-Fann and Kaneene, 1993). Fried (1991) estimated that in 1995 over 20% of the population of France would be drinking water exceeding the European Community's drinking water limit of 11.3 mg NO_3^--N/L. Increasing groundwater concentrations of NO_3^- are found in the United States, where 53% of the total population and 97% of the rural population obtain drinking water from ground water (U.S. Geological Survey, 1988).

Nitrate leaching to ground water depends predominantly upon the presence of soil nitrate and the rate of water movement through the profile, and also on other factors such as soil temperature, organic matter, and macroporosity. Because not all applied nitrogen is taken up by plants, excessive N fertilizer application increases leaching potential. Subsurface agricultural drainage, which is practiced to improve crop growth in poorly drained soils, speeds water movement through the soil profile and consequently nitrate leaching (Baker and Johnson, 1978).

Water table management has the potential to reduce N-pollution and increase crop yields. Water table management encompasses the use of controlled drainage and subirrigation. Under controlled drainage, water is prevented from exiting the soil profile by means of a plugged drainage outlet. The water table drops only due to evaporation and deep seepage. Subirrigation is achieved by

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installing a control structure at the drain outlet and supplying water to the drainage system via the control structure to maintain an elevated water table. When properly managed, subirrigation can maintain optimum moisture in the root zone and reduce leaching losses.

The design of appropriate systems for crop production and pollution control requires assessment of the impacts of alternative management systems. Due to the costs involved, field-scale experimental evaluation is somewhat limited in the questions it can answer in the short term. A cheaper and more flexible alternative is the use of computer simulation models.

Several studies have reported reductions of nitrogen losses in subsurface drainage waters ranging from 30% to 50% resulting from controlled drainage (Evans et al., 1995). Leaching losses of nitrate through subsurface drains are lower under controlled drainage due predominantly to reduced outflow and also due to soil denitrification enhancement by elevated water tables, which in turn leads to reduced soil nitrate levels (Evans et al., 1995).

DRAINMOD-N (Brevé et al., 1992, 1997a,b) is a field-scale model, based on DRAINMOD (Skaggs, 1978), a water table management model. DRAINMOD simulates tile flow, water table depth and soil moisture distribution in the soil profile, but not under frozen soil conditions. DRAINMOD is a widely used water table management model that has been shown to make accurate hydrologic simulations (Skaggs, 1982; Fouss et al., 1987). Solute transport algorithms have been added to DRAINMOD enabling it to simulate nitrate leaching, nitrogen transformations, N-uptake and mineralization (Brevé et al., 1992). The new model known, as DRAINMOD-N, which can be used to compute the movement and fate of nitrate in artificially drained agricultural soils, has only been validated on data from a few sites (Brevé et al., 1997a) DRAINMOD-N has recently been incorporated into a graphical user interface driven version of DRAINMOD, which also contains a salinity prediction component (Fernandez et al., 1998).

The primary objective of this study was to evaluate the performance of DRAINMOD-N in predicting water table depth, drain flow and NO_3^--N under free drainage and subirrigation 0.5 m from the soil surface, for conditions in Eastern Canada. A secondary objective was to explore the use within the model of another mathematical relationship for denitrification. This evaluation was done over a single growing season for monocropped corn grown on a sandy loam, a cropping situation common to much of the agricultural lands of the lower St. Lawrence valley in Eastern Canada.

Materials and Methods

Field Study

Field Site. A field study was conducted during the 1994 growing season on a 4.2-ha site located in Soulanges County, Quebec, about 30 km west of the Macdonald Campus of McGill University. Although the top soil was a well-drained Soulanges sandy loam (fine, silty, mixed, non-acid, frigid *Humaquept*), clay layers deeper in the soil profile, impeded natural drainage. Based on wells dug in the region and measurements of soil hydraulic conductivity, the impermeable layer was estimated to be 5 m deep. The surface topography was generally flat (average slope < 0.5%). The experimental site was under pasture before 1991, then subsequently it was under monocropped corn (*Zea mays* L.).

A randomized complete block design with three blocks and eight plots per block was used (Zhou et al., 1997). Blocks were arranged from east to west, with block A at the eastern end, bordered to the east by a 15-m strip of undrained land, followed by a 2.5-m deep × 3.0-m wide surface drain which collected runoff from the surrounding agricultural land (fig. 1). Blocks were separated by 30-m wide strips of undrained land. Individual plots were

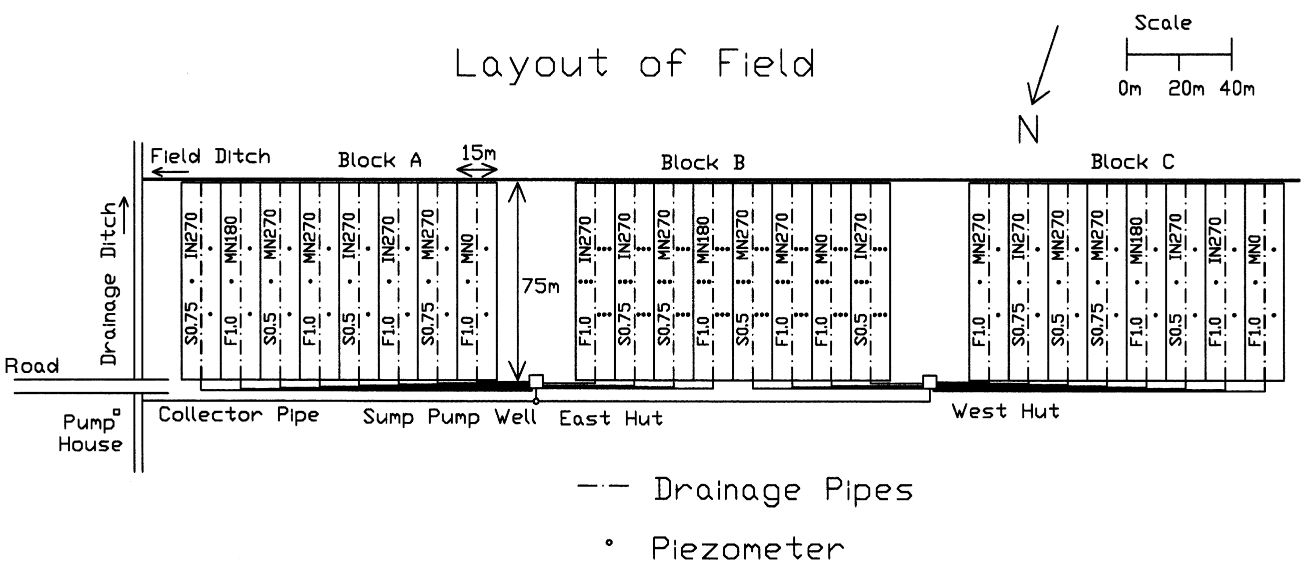

Figure 1–Schematic of three blocks of field plots with subirrigation 0.5 m or 0.75 m ($S_{0.5}$ or $S_{0.75}$) below the soil surface, or free drainage 1.0 m below the soil surface ($F_{1.0}$), combined with monocropped corn (M) or corn intercropped with ryegrass (I), and combined with three levels of N fertilization, 0 kg N ha^{-1}, 180 kg N ha^{-1}, or 270 kg N ha^{-1} (N0, N180, N270, respectively). Treatment plots for which DRAINMOD-N was tested were $S_{0.5}$ MN270 and $F_{1.0}$ MN270 in plots A and B.

separated by curtains of double thickness, 6-mil (0.6 mm) polyethylene sheeting installed to a depth of 1.5 m (Tait et al., 1995). A centrally located, 76-mm-diameter perforated drainage pipe, laid on a 0.3% slope, drained each plot. Each lateral pipe drained an area approximately 75 m long × 15 m wide. Drain flow from each pipe was directed to tipping buckets in heated buildings, allowing continuous drainage discharge measurements (Tait et al., 1995) and collection of water samples for flow weighted NO_3^--N determinations. Two cropping systems, monocropped corn (cv. Pioneer 3921) and corn intercropped with annual Italian ryegrass (*Lolium multiflorum* L. cv. Barmultra), were factorially combined with three water table depth (WTD) treatments: (1) conventional free outlet drainage (WTD about 1.0 m from the soil surface), or (2) subirrigation with design WTD at 0.5, or (3) 0.75 m below the soil surface. These six treatments received 270 kg N ha^{-1}. In freely draining monocropped plots, N rates of 0 and 180 kg ha^{-1} were also included. However, for this work the only variable studied was WTD (free drainage vs. 0.5 m WTD), both under monocropped corn, and both fertilized with 270 kg ha^{-1}, resulting in 2 plots in each of 2 blocks (A,B; see figure 1). While denitrification, drain flow and NO_3^--N losses were measured in block 3 (C; see figure 1), water table measurements were incomplete. Thus, only the complete data from blocks A and B were used to validate DRAINMOD-N.

Subirrigation. The subirrigation mechanism consisted of a water table control chamber with an inlet float valve and a pipe connecting the control chamber to the drainage lateral. An overflow pipe from the control chamber was directed to a tipping bucket. This overflow pipe was set 0.5 m below the soil surface. Design WTD were free drainage (about 1.0 m WTD below the soil surface; $F_{1.0}$), and subirrigation with design WTD of 0.5 m below the soil surface ($S_{0.5}$), for the subirrigation treatment. However, because of lateral seepage and evapotranspiration, the actual mean seasonal WTD measured in the field was about 0.7 m for the $S_{0.5}$ treatment. A $S_{0.5}$ plot in block C, that was not used in this model validation but was flanked with two plots subirrigated at a design WTD of 0.7 m had a substantially higher mean seasonal WTD than that of $S_{0.5}$ plots in blocks A and B, where they were flanked with two $F_{1.0}$ plots (data not shown). This suggests that while the plastic curtains were installed to well below the drains some lateral seepage occurred from subirrigated plots to adjoining freely draining plots. Subirrigation water, with no detectable NO_3^--N (< 0.1 mg/l), was obtained from a 25-m-deep high-production well. This water was sampled only once at the beginning of the study as it came from an extensive aquifer in the fractured bedrock (about 21-22 m deep), and no other nearby wells tapping this source have shown any detectable concentrations of NO_3^--N. Control valves on drain outlets were used to switch from free drainage mode to subirrigation. In subirrigation mode, water moved from the control chamber into the soil profile through the drainage line, until the WTD in the soil profile was the same as the elevation of the outlet in the control chamber. If infiltrating rain water caused a rise in water table above the design level, the excess would discharge to the tipping buckets for measurements.

Subirrigation was conducted from 25 May 1994 to 15 October 1994 (DOY 145-288). Before the start of subirrigation, the average WTD in all plots was about 0.8 m. In free drainage plots, the average WTD during the growing season was 1.0 m and deeper. Water table controls were removed in the fall of each year to drain the soil for harvest.

Agronomic Practices. On 31 May 1994 (DOY 151), corn was planted and all plots studied received 141 kg K ha^{-1} (supplied as K_2O) and 52 kg P ha^{-1} based on prior soil testing. All plots received P as ammonium phosphate (18-46-0), thus also providing 47 kg N ha^{-1}. An additional 233 kg N ha^{-1} were broadcast as ammonium nitrate (34-0-0) on 21 June 1994 (DOY 172), as well as 1.52 kg active ingredient (a.i.) ha^{-1} of atrazine (2-chloro-4-ethylamino-6-isopropylamino- 1,3,5 triazine) and 1.1 kg a.i. ha^{-1} basagran [bentazon; 3-(1-methyethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide] for weed control. Thus, the nitrogen fertilization rate was 270 kg N ha^{-1}, approximately 80-90 kg N ha^{-1} more than the locally recommended rate (Liang and Mackenzie, 1992). This excessive N fertilizer application was used to facilitate the evaluation of the effect of N application rate on NO_3^- loss from the different plots. Corn was harvested during the second week of October. The field was ploughed in the first week of November, incorporating all corn stover into the soil.

Field Measurements

Water Table and Tile Flow Monitoring. Perforated, 12-mm-diameter polyethylene pipes with a geotextile sleeve were installed vertically to a depth of 1.4 m in each plot to monitor WTD. In all plots single or sets of pipes for WTD measurement were installed at 25, 37.5, and 50 m along the length of the plot. In block A the pipes were installed at 3.5 m from the drain and the three measurements averaged to give an overall plot WTD. In block B pipes were installed at 1.5, 3.5, and 5.5 m from the central drain, resulting in nine pipes per plot. Again, WTD measurements were averaged for the plot.

The equipment for monitoring tile flow was operational from September 1993. A 500 mL sample was collected for each 500 L of drainage discharge, regardless of flow rate. Samples were collected in 20 L bottles to form composite samples. Sub-samples of 20 mL were collected once a week from the 20 L bottles. The sub-samples were filtered to remove suspended sediment and refrigerated at 4°C until analyzed. To calculate the total loss of NO_3^--N, its concentration in drain flow was multiplied by the drainage volume for the period since the last collection of samples. The NO_3^- levels were measured colorimetrically (method modified from Keeney and Nelson, 1982) using an autoanalyzer (Quik Chem @AE, Lachat Instruments, Milwaukee, Wis. USA).

Measurement of Denitrification. Denitrification rates (kg N d^{-1}) were measured fortnightly from 25 May 1994 to 12 October 1994 (DOY 145-285). Measurements were performed using the acetylene inhibition method (Aulakh et al., 1982). Aluminum cylinders (60 mm i.d. × 150 mm long), similar to those used by Liang and Mackenzie (1992), were used to obtain soil samples from the top 0.15 m of the soil profile. Each cylinder had small holes punched in the sides to allow gaseous diffusion. Cylinders were obtained from each replicate of the four treatment plots (2 WTD × blocks A and B) and placed in 2 L plastic jars. To inhibit nitrification and prevent reduction of N_2O to nitrogen, pure acetylene was injected into each jar to bring the acetylene to 5% (v/v). Samples were subsequently incubated for 24 h outdoors, under shade, providing similar temperature conditions to those in the field. Nitrous oxide (N_2O) in the head space was measured by collecting 1 mL gas samples from the jars and injecting them into a 5870 Series-II Hewlett-Packard gas chromatograph equipped with a Tracor electron capture linearizer and operated with a Tracor ^{63}Ni electron-capture detector (Aulakh et al., 1982). The quantity of N_2O emission per jar was calculated using the known volume of air inside the jar and N_2O concentration. Total N loss through denitrification was calculated on a per area basis (kg N ha^{-1}). Preliminary experiments showed that over 90% of N_2O production from denitrification occurred in the top 0.15 m of the soil. This is likely attributable to the organic carbon content below the 0.15 m depth of the profile being 1% or less; whereas, it was 5% in the surface layer, and the fact that the majority of the NO_3^- from applied fertilizer was in the surface layer. Thus it was assumed that denitrification in the top 0.15 m of the soil was highly representative of the overall rate of denitrification.

Water Balance. Pan evaporation was measured at Macdonald Campus using a class A evaporation pan. Evapotranspiration (ET, mm) was calculated from pan evaporation (ET_{pan}, mm) data, as follows:

$$ET = K_c K_{pan} ET_{pan} \qquad (1)$$

where K_c is the crop factor, and K_{pan} is the pan factor. Using FAO guidelines (Doorenbos et al., 1979), monthly values of K_c and K_{pan} were estimated for May through October (table 1). It was assumed that no difference in ET_{crop} existed between plots under $F_{1.0}$ and those under subirrigation. A water balance was carried out in block B where soil moisture data were available from July to October.

Table 1. Calculation of ET_{crop} base on pan evaporation data

Month	RH (%)	Wind Speed (km/d)	K_{pan}	E_{pan} (mm/d)	K_c	ET_{crop} (mm/day)
May	65	343	0.75	5.18	0.3	1.17
June	71	324	0.80	5.19	1.0	4.15
July	72	290	0.80	5.27	0.80	3.37
Aug	75	274	0.80	3.71	0.6	1.78
Sep	74	298	0.80	3.19	0.3	0.77
Oct	70	338	0.75	1.71	0.3	0.38

NOTE: RH = relative humidity; K_{pan} = pan coefficient; E_{pan} = pan evaporation; K_c = crop coefficient; ET_{crop} = crop evapotranspiration.

DRAINMOD

An evaluation of the original and a modified DRAINMOD-N was made by individually comparing observed tile flow, WTD, denitrification, and NO_3^- leaching from block A and block B with simulated data. Due to breaks in weather data collection at the field site, precipitation and temperature data required by DRAINMOD were obtained from the weather station at Côteau-du-Lac (about 5 km from the experimental site).

Model Characteristics and Modification. DRAINMOD-N is a field scale model used to compute the movement and fate of nitrate in artificially drained agricultural soils. It assumes that below the drains there is an impermeable layer reducing seepage. Therefore, DRAINMOD-N can simulate water and chemical movement in the soil profile in nonfrozen soil conditions, provided there is seepage or lateral water flow. It considers fertilizer N dissolution, supply of N by precipitation, runoff losses, N-uptake, mineralization, denitrification, and drainage losses of nitrogen (leaching). The model divides the soil profile, to a depth of 1.0 m (i.e., bottom of the field drains) into segments of 50 mm and calculates water and solute flow based on the advective-dispersive-reactive equation:

$$\frac{\partial\left(\theta\left[NO_3^-\right]\right)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial\left(\left[NO_3^-\right]\right)}{\partial z}\right) - \frac{\partial\left(q\left[NO_3^-\right]\right)}{\partial z} + \Gamma \qquad (2)$$

where t is time (T), z is depth below the soil surface (L), θ is the volumetric water content (L^3 L^{-3}), q is the vertical flux (L T^{-1}), D is the coefficient of hydrodynamic dispersion (L^2 T^{-1}), and Γ is a source/sink term (M L^{-3} T^{-1}) comprising net mineralization, denitrification, N-uptake, runoff, nitrogen deposition, and dissolved nitrogen fertilizer.

DRAINMOD-N uses functional relationships to compute denitrification, mineralization and N-uptake. Mineralization (Γ_{mnl} – M L^{-3} T^{-1}) is calculated (eq. 3) as a zero order process depending on a rate coefficient, soil water content, temperature, bulk density, and the concentration of organic nitrogen (Brevé, 1994):

$$\Gamma_{mnl} = K_{mnl}\, f_{mnl\text{-}\theta}\, f_{temp}\, \rho\, O_n \qquad (3)$$

where K_{mnl} is the mineralization rate coefficient (T^{-1}), $f_{mnl\text{-}\theta}$ and f_{temp} are dimensionless soil-water content and temperature adjustment factors, respectively, ρ the soil bulk density (M L^{-3}), and O_n represents the concentration of organic nitrogen (M M^{-1}).

DRAINMOD-N estimates $\Gamma_{den\text{-}B}$ by a first-order process, its rate being directly related to the nitrate concentration [NO_3^--N] in the soil profile, as well as other factors (Brevé, 1994):

$$\Gamma_{den\text{-}B} = BK_{den}\, f_{den\text{-}\theta}\, f_{temp}\, f_z\, \theta\, [NO_3^-\text{-N}] \qquad (4)$$

where $\Gamma_{den\text{-}B}$ is the denitrification rate (M L^{-3} T^{-1}), BK_{den} the denitrification rate constant (T^{-1}), and f_z is a dimensionless depth factor that reflects the decrease in organic matter with depth. Common to the mineralization and denitrification formulae, are the dimensionless soil-water content temperature and depth adjustment factors $f_{den\text{-}\theta}$, f_{temp}, and f_z:

$$f_{den\theta} = \frac{\theta - \theta_{den}}{\theta_{sat} - \theta_{den}} \qquad (5)$$

$$f_{temp} = Q_{10}\left(\frac{T - t_b}{10}\right) \qquad (6)$$

$$f_z = e^{\alpha Z} \qquad (7)$$

where θ_{sat} and θ_{den} are saturated moisture content (soil porosity, $L^3\,L^{-3}$) and the water content below which denitrification rate is zero ($L^3\,L^{-3}$), respectively. While soil porosity was measured in the lab, θ_{den} is assumed by DRAINMOD-N to be equal to be 90% θ_{sat}. Variable Q_{10} is the change of mineralization or denitrification rate associated with a 10°C change in soil temperature (unitless temperature coefficient). In this study a Q_{10} value of 3.0 was used (Ambus, 1993). The base temperature for microbial denitrification is denoted as t_b and was assumed to be 5°C in this study. The literature suggests that when soil temperature is below 5°C, little denitrification occurs (Webster and Goulding, 1989). In equation 7, α is an empirical unitless constant ranging from 0.02 to 0.05 (Brevé et al., 1997b), based on a best fit relationship between observed organic N concentration across the soil profile and maximum organic N ($M\,M^{-1}$) in the top layer. The denitrification coefficient in equation 4 (BK_{den}) was derived graphically from plots of field denitrification against soil nitrate data.

Input Parameters. DRAINMOD-N requires general input parameters as well as inputs of soil properties such as porosity, wilting point, bulk density, and organic matter (table 2). Hydraulic conductivity was determined by the auger hole method, while moisture characteristic curves for the soil were determined using the pressure plate method (Mousavizadeh, 1992).

Simulations were performed for the growing season of 1 May to 30 November (DOY 121-334) 1994. Corn was planted on 25 May, and the period of growth lasted for 130 days (table 2). For a maximum rooting depth of 0.8 m, 60% of total root bulk for corn occurs within the top 0.3 m of the soil profile (Mengel and Barber, 1974). Based on this information the effective rooting depth for the growing season was estimated at 0.3 m (table 2). In the experimental field, after heavy rainfall, water typically remained in a few shallow pools . Therefore, a depression surface storage of 1.5 cm was selected based on the DRAINMOD users' guide (Skaggs, 1980).

The mineralization coefficient was estimated from the literature (Brevé, 1994). It was assumed that precipitation contributed negligibly to soil nitrogen, and that the organic-N content was 2800 mg/kg soil, a typical value in southern Quebec (Liang and Mackenzie, 1992). Grain corn yield in conditions of non-limiting fertilizer and soil moisture was estimated at 10 Mg/ha (Liang and Mackenzie, 1992) and considered the potential corn yield (table 2). NO_3^--N concentration measured in the bulk soil during spring, just before planting was 30 mg NO_3^--N/L and represented initial N. Mean percentage of nitrogen in corn (leaves, straw and grain) was 1.5%, and was not influenced by water table treatment (Liang and Mackenzie, 1992). In DRAINMOD-N, soil temperature data used in the calculation of mineralization and denitrification are estimated using an equation similar to that of Rijtema and Kroes (1991):

Table 2. DRAINMOD-N input parameters

Parameter	Value	Units
Drainage System		
Drain depth	1.00	m
Depth to impermeable layer	5.00	m
Effective radius	35	mm
Surface storage	15.00	mm
Distance between drains	15.00	m
Heat index	45.00	
Weir setting for subirrigation	0.50/0.75	m
Soil Properties		
θ_{sat} (saturated soil moisture content)	0.470	m^3/m^3
θ_{wp} (soil moisture content at wilting point)	0.325	m^3/m^3
ρ (bulk density)	1.5	Mg/m^3
Hydraulic conductivity	5.3×10^{-6}	m/s
Clay	31	%
Silt	34	%
Sand	35	%
Average yearly temperature (T_a)	10	°C
Wave amplitude (A_0)	20	°C
Wave damping depth (D_m)	1.0	m
Wave phase shift (ϕ)	250	days
Q_{10}	3	
t_b (base temperature)	5	°C
Depth of soil	1	m
Thickness of soil layers	0.05	m
Corn Production		
Desired planting date	25 May	
Length of growing season	130	days
Effective rooting depth	0.3	m
N-fertilizer input	270	kg/ha
Date of application	25 May 10 June	
Depth of fertilizer incorporation	0.1	m
Nitrogen Dynamics		
N from rain	0.0001	mg/L
Organic N	2800	μg/g soil
K_{min}	1×10^{-5}	day^{-1}
Potential yield	10000	kg/ha
Initial N	30.0	mg/L
Denitrification coefficients:	0.0012	day^{-1}
BK_{den} $F_{1.0}$	0.0036	day^{-1}
$S_{0.5}$	0.12	mg/L/day
JK_{den} $F_{1.0}$	0.36	mg/L/day
$S_{0.5}$	1.5	%
N content of plant		

$$T = T_a - A_0\left\{ e^{-\frac{z}{D_m}} \cos\left[\frac{2\pi}{365}\left(t_j - \phi\right) - \frac{z}{D_m}\right]\right\} \qquad (8)$$

where T_a is the average yearly air temperature (°C), A_0 is the amplitude of the temperature wave (°C), D_m is the wave damping depth (L), ϕ is the phase shift (T), t_j is time after start of simulation (T), while z denotes the depth (L) below the soil surface (table 2). For a fixed depth of 0.15 m, these parameters resulted in a satisfactory simulation of temperature (fig. 2).

Simulated and measured WTD, drainflow, denitrification and nitrate leaching were compared using the standard error, defined as follows:

$$s = \sqrt{\frac{\sum_{i=1}^{i=n}\left(Y_{i,\,model} - Y_{i,\,obs}\right)^2}{n}} \qquad (9)$$

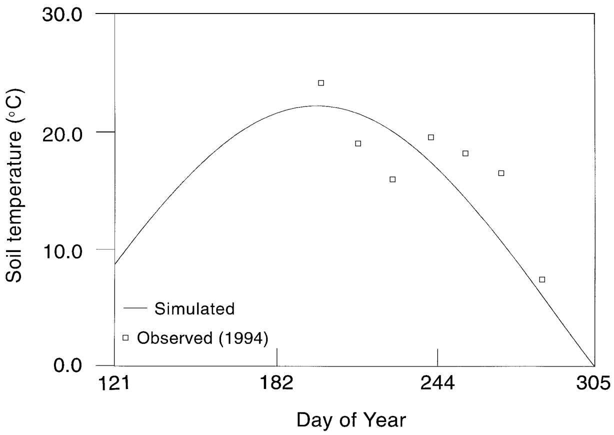

Figure 2–Simulated and observed soil temperature (°C) for a one year period starting from 1 May 1994, at a depth of 0.15 m.

where n is the number of observations, and $Y_{i,\ model}$ and $Y_{i,\ obs}$ are simulated and observed values, respectively.

Results and Discussion

Model Performance

Simulated WTD was close to the observed, with a standard error from 160 to 210 mm. Simulated WTD deviated most from observed values during August and September. During those periods the model tended to predict shallower WTD in $S_{0.5}$ plots than were measured and deeper WTD in $F_{1.0}$ than were measured plots, particularly for block A (fig. 3). Overall the prediction of WTD was quite good given the seasonal variability of measured WTD.

The $F_{1.0}$ plot in block A (fig. 1) exhibited flow during most of the summer, a period during which little or no flow was observed in other plots. Negative tile flow indicated that there was net water input by subirrigation, while positive flow indicated net water output from the plots. The standard error in this case was 2.1 mm/day compared to a standard error of 1.0 mm/day for $F_{1.0}$ in block B. Thus, DRAINMOD-N underestimated drain flow in this plot (fig. 4). This could be due to seepage from the two bordering plots, each subjected to the $S_{0.5}$ treatment. The smaller standard error in the case of $F_{1.0}$ in block B was probably because it was bordered on one side by a $F_{1.0}$ plot. Therefore, there may have been less water leakage into this plot from neighboring plots. This was not the case in block B.

The standard errors for NO_3^- leaching losses ranged from 4.9 to 8.0 kg N/ha under $S_{0.5}$, and from 1.4 to 5.1 kg N/ha under $F_{1.0}$ (table 3). Drainage loss of NO_3^--N was higher in $F_{1.0}$ than in $S_{0.5}$ (fig. 5). Annual losses were about 21 kg N/ha and 35 kg N/ha for $F_{1.0}$ and $S_{0.5}$ plots, respectively. The model predicted cumulative NO_3^- leaching within 5 to 10% for the $S_{0.5}$ and $F_{1.0}$ treatments in block B, but overestimated it by 40 to 60% for the $S_{0.5}$ treatment in block A (fig. 5). The model similarly overestimated (40-65%) cumulative NO_3^- leaching for the $F_{1.0}$ treatment in block A, during the summer months, but gave good (within 5%) estimates for September and October.

DRAINMOD-N underestimated cumulative denitrification, particularly after DOY 180 (fig. 6), with a standard error in the range of 4 to 20.1 kg N/ha (table 3).

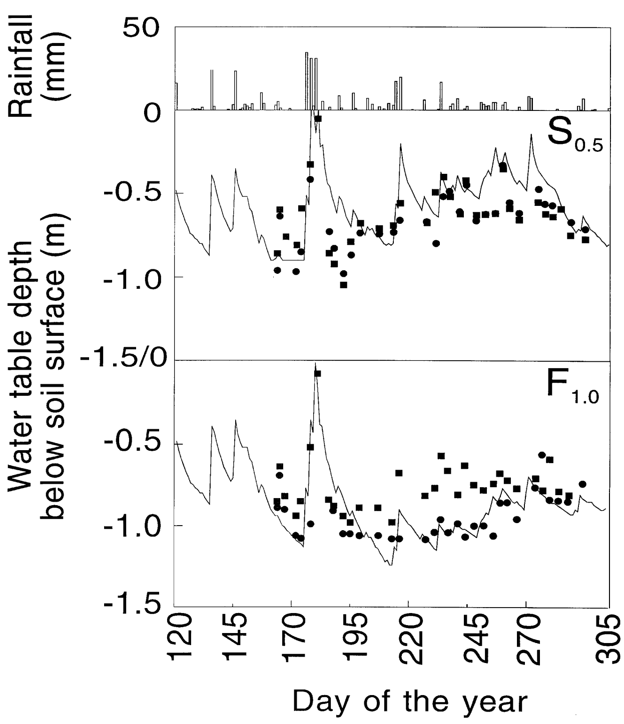

Figure 3–Comparison of observed water table depth (m) for Block A (n), and Block B (l); and water table depth simulated with the modified DRAINMOD-N (____), for freely drained plots ($F_{1.0}$), and plots subirrigated to 0.5 m from the soil surface ($S_{0.5}$).

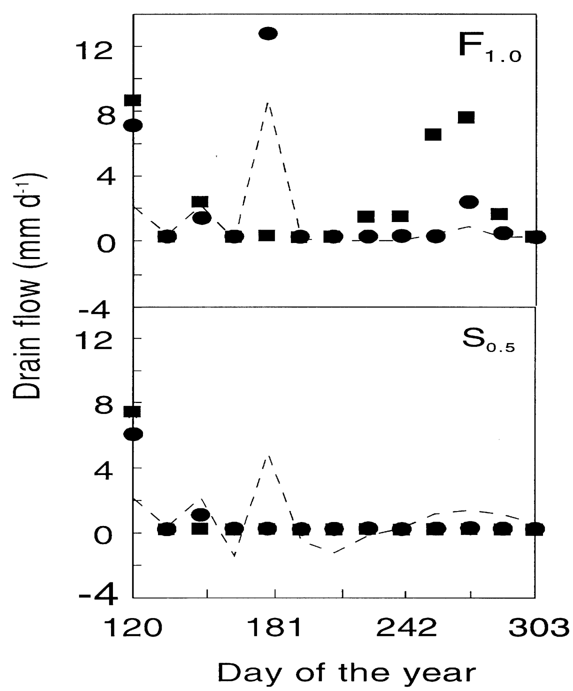

Figure 4–Comparison of observed drain flow (mm d^{-1}) for Block A (n), and Block B (l); and drain flow simulated with the modified DRAINMOD-N (_ _ _) for freely drained plots ($F_{1.0}$), and plots subirrigated to 0.5 m from the soil surface ($S_{0.5}$).

Table 3. Summary of standard errors (S.E., eq. 14) for leaching and denitrification, simulated by the original and modified DRAINMOD-N for blocks A and B

		Simulated vs Observed, S.E.			
Treatment/ Block	DRAIN-MOD-N Version	Cumulative Leaching Losses (kg N/ha)	Cumulative Denitri-fication (kg N/ha)	Drain Flow* (mm/d)	Water Table Depth (mm)
$S_{0.5}$A	Modified	8.0	11.4	1.2	213
	Original	8.1	20.1	1.2	213
$S_{0.5}$B	Modified	4.9	6.0	2.1	194
	Original	5.0	15.3	2.1	194
$F_{1.0}$A	Modified	5.1	10.0	2.1	212
	Original	5.2	13.1	2.1	212
$F_{1.0}$B	Modified	1.4	1.7	1.0	161
	Original	1.4	4.0	1.0	161

* DRAINMOD-N did not consider seepage.

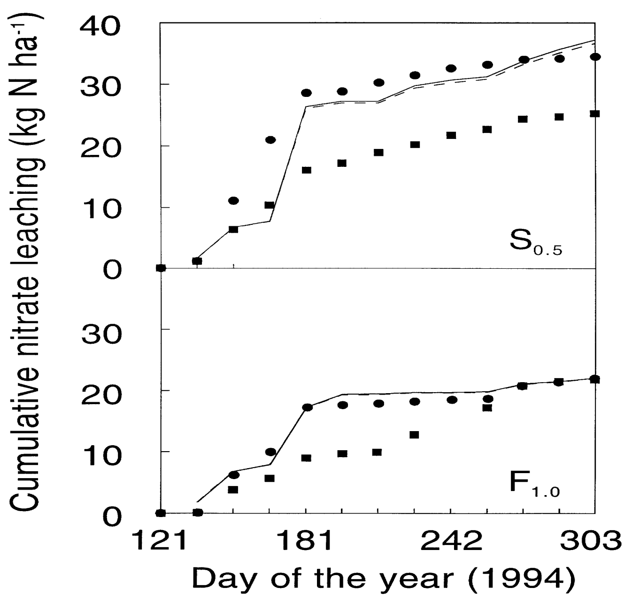

Figure 6–Comparison of observed cumulative denitrification (kg N ha^{-1}) for Block A (n), and Block B (l); and cumulative denitrification simulated with the original DRAINMOD-N model ($\Gamma_{den\text{-}B}$ ____), or modified DRAINMOD-N model ($\Gamma_{den\text{-}J}$ _ _ _), for freely drained plots ($F_{1.0}$), and plots subirrigated to 0.5 m from the soil surface ($S_{0.5}$).

The DOY 180 coincided with a large precipitation event and came some 10 days after the second fertilizer application. By day 270, DRAINMOD-N underestimated cumulative $\Gamma_{den\text{-}obs}$ by 80 to 83% and 64 to 80% for $S_{0.5}$ and $F_{1.0}$, respectively (fig. 6). Generally, Γ_{den} simulations for plots in block B were more accurate than for block A plots (fig. 6). This was likely due to greater seepage in block A.

Early in the growing season, the trend of simulated denitrification resembled that of observed cumulative denitrification in all cases, though perhaps simply because at such low values variability was not apparent. However, in the summer months there was a greater deviation between observed and simulated cumulative denitrification. For instance, during the summer, observed denitrification in $F_{1.0}$ in block A was close to four- to five-fold higher than the simulated value. In $F_{1.0}$ in block B, the agreement between simulated and observed cumulative denitrification was better (at worst about two-fold). Apparently, water seepage into $F_{1.0}$ in block A from surrounding subirrigated plots during the summer seems to have made these plots wetter than expected, therefore causing more denitrification in the plot (fig. 1).

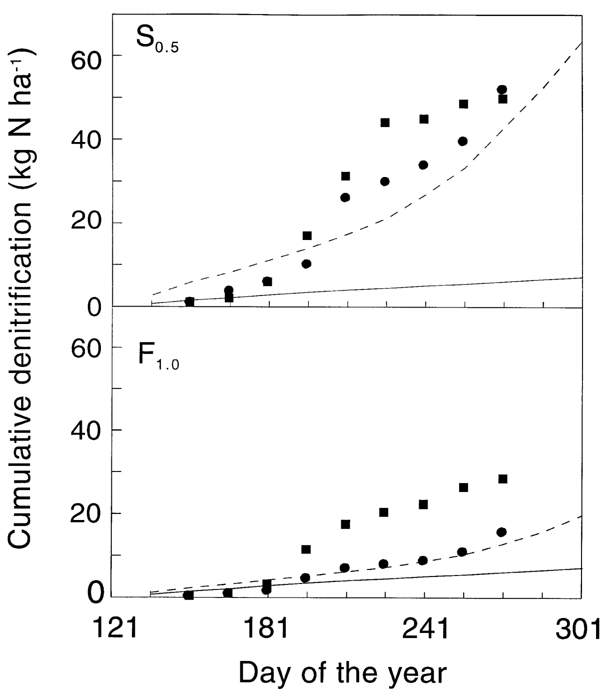

Figure 5–Comparison of observed cumulative nitrate leaching (kg N ha^{-1}) for Block A (n), and Block B (l); and cumulative nitrate leaching simulated with the original (____) or modified (_ _ _) DRAINMOD-N models for freely drained plots ($F_{1.0}$) and plots subirrigated to 0.5 m from the soil surface ($S_{0.5}$).

Sensitivity analyses for ET_{crop}, initial N, and BK_{den} revealed that a 30% change in ET_{crop} for July (3.37 ± 1.01) could cause a 30% change in simulated drain flow as well as 40% change in simulated leaching (fig. 7). ET_{crop} had little effect on denitrification. A 100% increase in initial N (from 30 to 60 mg/L) resulted in 75% and 20% increases in leaching and denitrification, respectively. Brevé (1994) has shown BK_{den} to influence not only denitrification, but also leaching. In the present study BK_{den} affected only denitrification, where a 100% increase in BK_{den} (from 0.0036 to 0.0072 day^{-1}) resulted in an almost 100% increase in denitrification. The BK_{den} parameter may have had little effect on leaching losses because nitrate N was in abundant supply, thus making denitrification relatively insignificant.

Modified DRAINMOD-N

Soil [NO_3^--N] showed poor correlation with measured denitrification (fig. 8). The original DRAINMOD-N poorly simulated denitrification as it assumed denitrification to be a first order process. Johnsson et al. (1987) used the Michaelis-Menten relationship, which does not restrict denitrification to a single specific order of kinetics. In their formula, denitrification rate (DEN_J) is expressed as:

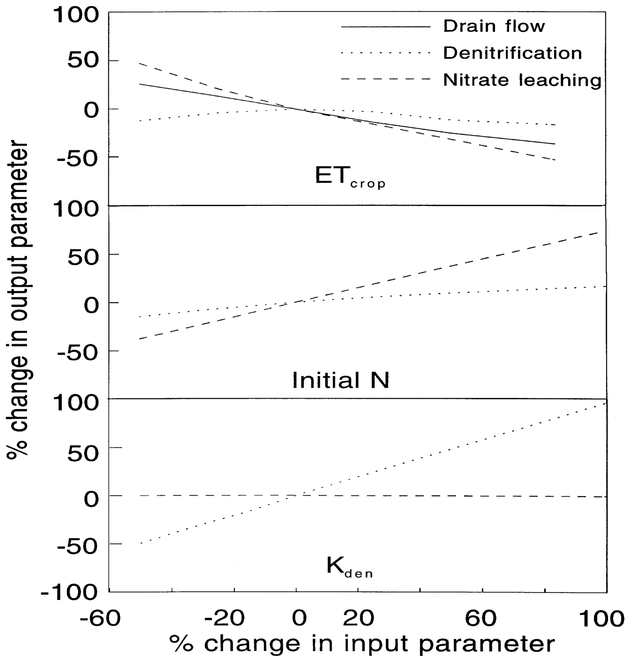

Figure 7–Sensitivity analysis - percent change in output parameters, drain flow, denitrification, and nitrate leached to drains, due to changes in input parameters, crop evapotranspiration (ET_{crop}), initial N, and denitrification rate coefficient (K_{den}), for the modified version of DRAINMOD-N.

$$\Gamma_{denJ} = JK_{den} f_{den\theta} f_{temp} f_z \left(\frac{[NO_3^- \text{-N}]}{[NO_3^- \text{-N}] + K_m} \right) \quad (10)$$

where $\Gamma_{den\text{-}J}$ is the denitrification rate (M L^{-3} T^{-1}) according to Johnsson's equation, JK_{den} the denitrification rate constant according to Johnsson's equation (T^{-1}), and K_m is the [NO_3^--N] (M L^{-3}) for a denitrification rate equal to half of maximum (Johnsson et al., 1987). The last term in equation 10 approaches unity as [NO_3^--N] increases. Therefore, since the last term increases with increasing [NO_3^--N], equation 10 tends to simulate a zero order process at high [NO_3^--N]. However, at low [NO_3^--N] it simulates a first order process. In the absence of NO_3^--N, denitrification would cease, but when NO_3^--N is non-limiting, the denitrification rate would depend on other factors such as soil moisture content, temperature or organic carbon.

Pearson correlation coefficients were calculated for the relationship between denitrification measured in the field ($\Gamma_{den\text{-}obs}$) and $\Gamma_{den\text{-}B}$ (eq. 4), and between $\Gamma_{den\text{-}obs}$ and Michaelis-Menten expression of Johnson ($\Gamma_{den\text{-}J}$; eq. 10). While both were significant at P ≤ 0.0001, the Pearson correlation coefficient values for $\Gamma_{den\text{-}J}$ were no lower than those for $\Gamma_{den\text{-}B}$ (table 4). This and in particular figure 6 showed that replacing equation 4 with the Michaelis-Menten equation, could improve the simulation of denitrification. The goodness of fit was higher in $S_{0.5}$ plots than in $F_{1.0}$ plots (table 4).

Table 4. Pearson correlation coefficients between measured denitrification for both blocks A and B, and denitrification as calculated by the expressions of Johnsson et al. (1987) or Brevé (1994)

Water Table Management (depth from soil surface)	Denitrification Expression: Johnsson et al. (1987) $\Gamma_{den\text{-}J}$	Brevé (1994) $\Gamma_{den\text{-}B}$
Free drainage (1.0 m)	0.41	0.38
Subirrigation (0.50 m)	0.55	0.55

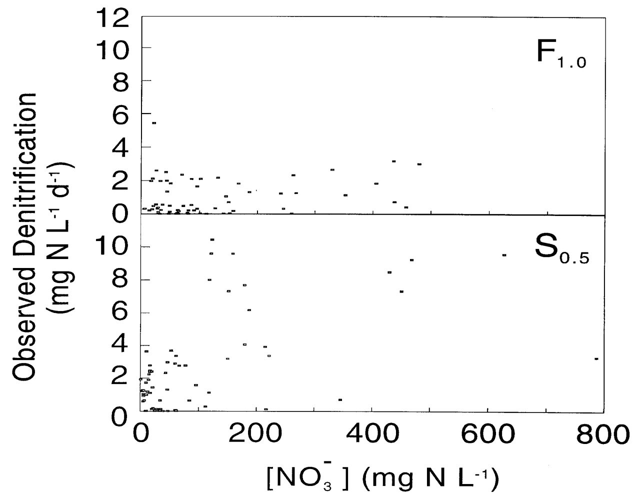

Figure 8–Relationship between observed denitrification rate (mg N L^{-1} d^{-1}) and nitrate concentration (mg N L^{-1}) in the top 0.15 m of the soil profile, for a freely drained plot ($F_{1.0}$), and a plot subirrigated to a water table depth of 0.5 m below the soil surface ($S_{0.5}$).

The JK_{den} values used in the improved model were determined by plotting $\Gamma_{den\text{-}obs}$ against $\Gamma_{den\text{-}J}$ and calculating the slope of the best line of fit. Similarly, BK_{den} values were obtained by plotting $\Gamma_{den\text{-}obs}$ against values from equation 4 and calculating the slope. For $F_{1.0}$ and $S_{0.5}$, JK_{den} values were 0.12 and 0.36 mg N L^{-1} d^{-1}, respectively (table 2). The shallower the water table, the higher the denitrification coefficient. The corresponding BK_{den} values were 0.0012 and 0.0031 d^{-1} (table 2).

Brevé's denitrification equation in the original DRAINMOD-N was replaced with the Michaelis-Mentes equation (Johnsson et al., 1987). The original and modified DRAINMOD-N were used to simulate denitrification and leaching, which were compared with observed data.

The modified model underestimated cumulative denitrification at day 270 by only about 15% for $S_{0.5}$ in both block A and B, and $F_{1.0}$ in block B, and by at most 50% for $F_{1.0}$ in block A (fig. 6). Thus, at least for block B the modified model gave much better predictions of cumulative denitrification than the original DRAINMOD-N.

Conclusions

DRAINMOD-N predicted water table depth, drainflow, and cumulative nitrate leaching from both conventionally drained and subirrigated monocropped corn plots fairly well (±20%). However, the assumption in DRAINMOD-N that denitrification is a first-order reaction did not adequately describe the measured relationship between denitrification and soil nitrate concentration, showing errors of as high as 60%. Replacing the existing denitrification equation with a Michaelis-Menten relationship that accommodates both first and zero order processes depending on the concentration of nitrate N in the soil profile resulted in a more realistic simulation of cumulative denitrification. While these differences in prediction of denitrification are large, since denitrification affects a relatively small portion of the N on a total mass basis, the effects of this correction are small in overall N dynamics.

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