Simulating effects of MERN and other BMPs on subsurface drainage water quality and crop yield in southern Ontario

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[1]*Ministry of Agriculture, Food and Rural Affairs, Woodstock, Ontario N4T 1W2, Canada; and* [2]*School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, Canada. *Email: rrudra@uoguelph.ca*

McKague, K., Rudra, R.P., Ahmed, S.I., Gharabaghi, B. and Ogilvie, J.R. 2006. **Simulating effects of MERN and other BMPs on subsurface drainage water quality and crop yield in southern Ontario**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada 48: 1.31 - 1.40. In Ontario, the Most Economic Rate of Nitrogen (MERN) application is being promoted to achieve optimal crop production. However, the potential long-term environmental impact of such nitrogen (N) application rates is not yet known. The Root Zone Water Quality Model (RZWQM) was used to evaluate the long-term effect of MERN, side-dress versus pre-plant N application, split N applications over the growing season, pre side-dress N test (PSNT), and reduced N application through crop rotation on crop yield and nitrate-nitrogen (NO_3-N) loss through the tile drainage system. The results indicate that MERN for corn production fluctuates significantly from year-to-year in response to annual climatic conditions. However, the long-term average MERN of 184 kg/ha was close to current corn production recommendation of 175 kg/ha. The results of this study also indicate that planting time N application could result in slightly (1.4%) higher NO_3-N losses in the tile outflow than side-dress application of nitrogen. Split applications of N could lead to 11.3% reduction in long-term annual NO_3-N loads but this practice can also result in about 7.6% decline in long-term corn yield compared to MERN application at planting time. Overall, this study shows that under Ontario conditions timing and rate of nitrogen applications are important in minimizing the amount of NO_3-N losses to subsurface drains, particularly during the late winter and spring seasons. **Keywords:** modelling, MERN, RZWQM, BMP, nitrogen, water quality.

En Ontario, le taux de fertilisation azotée le plus économique (MERN) est celui qui est recommandé pour obtenir une récolte optimale. Cependant, les impacts environnementaux potentiels à long terme de tels taux d'application d'azote (N) n'est pas encore connu. Le modèle de prédiction de la qualité d'eau dans la zone racinaire (RZWQM) a été utilisé pour évaluer l'effet à long terme du MERN lors d'épandage du N en bandes en post-semis comparativement à un épandage en pré-semis, des épandages fragmentés durant la saison de croissance, le test d'azote avant l'application au semis (PSNT) et des épandages à taux réduits de N en rotation de cultures basés sur le rendement des cultures et les pertes en nitrates (NO_3-N) par le système de drainage souterrain. Les résultats montrent que le MERN fluctue de manière significative pour la production de maïs d'une année à l'autre en fonction des conditions climatiques annuelles. Cependant, la moyenne à long terme MERN de 184 kg/ha était près de la recommandation courante de 175 kg/ha pour le maïs. De plus, les résultats de cette étude indiquent que l'épandage de N au semis entraîne des pertes de NO_3-N un peu plus élevée (1,4%) à la sortie des drains qu'un épandage de N en post-semis. Des épandages fragmentés de N pourraient entraîner une réduction de 11,3% des charges annuelles à long terme de NO_3-N mais cette pratique peut aussi résulter en une réduction du rendement de maïs à long terme d'environ 7,6% comparativement à l'épandage MERN au semis. De manière générale, cette étude montre que sous les conditions de l'Ontario, le moment et le taux d'épandage de l'azote sont importants pour minimiser les quantités de NO_3-N perdues dans les drains souterrains particulièrement tard durant l'hiver et au printemps. **Mots clés**: modélisation, MERN, RZWQM, BMP, azote, qualité de l'eau, bonnes pratiques agricoles

INTRODUCTION

Corn production systems are one of the dominant users of manure and commercial fertilizers as sources of nitrogen (N). In Ontario, about one quarter of the tilled agricultural land is under corn production and the recommended nitrogen application rates for growing corn range from 90 to 210 kg N/ha (OMAFRA 2002a). Specific field recommendations depend on the expected corn yield, the nitrogen-to-corn price ratio, and the geographic location, as well as previous crop and management history of the field.

Reduced nitrogen use efficiency results in an increase in the risk of nitrogen loss to the environment. The amount of nitrate-nitrogen (NO_3-N) not used by the crop may move to groundwater aquifers through deep percolation or to surface water bodies through tile drainage systems (Ng and Rudra 2001). Recent studies indicate that the NO_3-N level in the surface water is rising due to agricultural practices. The annual nitrate flux from the Mississippi River system to the Gulf of Mexico has approximately tripled during the last 30 years (Goolsby et al. 2001). A study by Randall and Mulla (2001) also indicated that the principle sources of N loading are predominantly agricultural land use activities and tile drainage in the humid regions of the Mississippi basin.

Similar concerns of water pollution from agricultural production systems also exist in Ontario. Tile drainage is a very common water management practice in Ontario. About 60 to 70% of crop land under corn and soybean cultivation has been estimated to be tile-drained (Personal Communication, S. Vander Veen, Drainage Coordinator, Ontario Ministry of Agriculture and Food, Guelph, ON). Fleming and Fraser (1999), in reviewing water quality data from watersheds in southern Ontario, observed that nitrate levels in surface waters have been rising steadily since the 1960's and the highest nitrate levels are found to be in predominantly agricultural watersheds. Beauchemin et al. (1998) also reported high total phosphorus concentrations in subsurface drainage water in Quebec. Tan et al. (2004) indicated that the subsurface drainage flow weighted mean NO_3-N concentration could reach 17.5 mg/L, almost twice the Canadian drinking water standard of 10 mg/L.

Best management practices (BMPs) have been promoted as a tool to balance the agricultural production need for fertilizer N with the parallel need to protect water quality. For example, spring application of N fertilizer could result in a 14% reduction in the NO_3-N losses to the subsurface drainage water compared with fall-applied N (Randall and Vetsch 2005). Smiciklas and Moore (2004) also reported that the fall application of N (anhydrous ammonia) results in about 50% more NO_3-N losses to subsurface drainage water as compared to the same rate of fertilizer N application during spring. Jaynes et al. (2004) indicated that late spring application of N fertilizer could result in a significant reduction in net N applications compared with standard (pre-plant N application) practice adopted by the farmers. Adoption of late spring application could also result in more than 30% reduction in the NO_3-N concentrations in surface water compared to pre-plant application.

Scharf et al. (2005), while evaluating the optimal N fertilizer rate for corn production, indicated that further research is needed to develop systems to determine economically feasible and environmentally sustainable N application rates. In recent years, many jurisdictions, including Ontario, have developed computer-based tools to prepare nutrient management plans (OMAFRA 2001). In essence, nutrient management planning tools incorporate the methods available for estimating the most economic rate of nitrogen (MERN). Ontario nutrient management planning software (NMAN) assumes that N application matching the MERN will optimize crop yield and simultaneously help to minimize environmental impact. However, the effectiveness of these recommended rates to meet the yield and environmental objectives is not always clear. Also, the effect of variation of annual climatic characteristics on MERN is not yet known.

Increasing the proportion of legumes in a crop rotation system can reduce the amount of N application and NO_3-N losses in subsurface drainage water. A long-term study to quantify the effect of crop rotation and N fertilization practices on crop yield indicated that crop rotation systems are more effective in reducing long-term yield variability than monoculture systems (Gary 2000). In another study, Kladivko et al. (2004) reported that reduced N application rate and addition of a cover crop in the corn-soybean rotation system can significantly reduce the NO_3-N concentrations in the tile outflows. Kanwar et al. (2005) also suggested that applications of traditional and non-traditional crop rotation systems have potential to reduce NO_3-N leaching to the shallow groundwater.

The field evaluation of the relative benefits of BMPs is costly and time-consuming (Yiridoe et al. 1997); therefore, the use of computer modeling approaches has become popular among environmentalists and researchers (Pearson et al. 1996). Rudra et al. (2005) used the computer modelling approach to simulate nutrient and pesticide transport in subsurface drains and concluded that modeling approaches provide a useful tool for management of soil-water quality. In addition, many other researchers have suggested that agricultural system modeling approaches are the most appropriate tool for cost effective and rapid evaluation of the effectiveness of BMPs under a wide range of conditions (Addiscott et al. 1991; Magdoff 1991; Ma et al. 2000; Bakhsh et al. 2001).

In recent years, numerous computer models have been developed to evaluate the impact of BMPs on soil-water quality. Broadly, these models can be classified as field scale models or watershed scale models. Alexander (1988) developed ADAPT (Agricultural Drainage and Pesticide Transport) to simulate the quality and quantity of tile flows with watertable management systems. Wagenet and Hutson (1989) developed LEACHM (Leaching and Estimation and Chemistry Model) to estimate the water flow and chemical transport through the soil profile. Workman and Skaggs (1990) developed a water-management model capable of simulating preferential flow. DRAINMOD developed by Skaggs (1982) has the potential to simulate quality and quality of tile outflows. The new version of RZWQM (USDA-ARS 1992) also has the capability to simulate the subsurface drain flow and to evaluate the impacts of alternative crop management practices on crop productivity and environmental quality (Ahuja et al. 2000). Bakhsh et al. (2001) also suggested that RZWQM can be used to simulate the effect of N application rates on NO_3-N losses in the subsurface drainage water.

The main objective of this study was to evaluate the long-term relative environmental benefits and production impacts of commonly promoted N fertilization BMPs for corn production in Ontario. The specific objectives were to evaluate the impact of application of MERN, the side-dress application of N, the split applications of N over the growing season, the N application rate based on the pre-side-dress nitrogen test (PSNT), and the reduced N application through crop rotation on crop yield and tile drainage water quality.

METHODOLOGY

The RZWQM was selected as a simulation tool in this study because this model has already been extensively used in various climatic regions of the USA (Singh et al. 1996; Jaynes and Miller 1999; Ma et al. 2000; Bakhsh et al. 2001) and in Canada (Madani et al. 2002) for water quality studies.

Description of RZWQM

RZWQM has six main components or processes that constitute the core of the model. It includes physical processes, soil chemical processes, nutrient processes, pesticide processes, plant growth processes, and management processes. The physical and soil chemical process components simulate number of interrelated hydrologic functions needed to predict nitrogen fate and crop growth. These include the infiltration of precipitation into the soil matrix or its movement through macropores, the transfer of chemicals from surface soil to runoff, the redistribution of soil-water and chemicals after infiltration, plant water uptake, and evaporation. The nutrient sub-model in RZWQM simulates carbon and nitrogen cycles in the soil system. The pesticide component of RZWQM simulates the fate of pesticides applied. Plant growth processes are simulated by a generic crop production sub-model. It predicts the relative response of common field crops (corn and soybeans) to changes in environmental conditions and management practices (Hanson 2000). The management component simulates the effect of practices, such as tillage, fertilizer application rate, timing of manure application, and irrigation on plant growth and root zone processes. A detailed description of RZWQM has been given by Ahuja et al. (2000).

Calibration of RZWQM

Study sites The data collected during the Ontario Green Plan - Systems Comparison Program were used for the calibration of RZWQM. During this program, 16 fields were monitored on commercial farms in southwestern Ontario (Sadler-Richards 1998). All the monitored sites followed either a corn-soybean or a corn-soybean-winter wheat rotation. Half of the sites were under no-tillage practices and the remaining half under conventional tillage practices.

The NBS site (0.77 ha) near London, Ontario, was selected for calibrating RZWQM for no-till conditions. The calibration site is situated on a tile drained Listowel silt loam soil and was under no-till for seven years prior to this study. This site was monitored for three growing seasons (one full crop rotation cycle). Average land slope in the monitored area was estimated to be 1.4%. The soybeans were planted in 1994, winter wheat in 1994/1995, and grain corn in 1996. The TGW site (2.92 ha), under conventionally management practices, was selected for validation of RZWQM. The field is systematically tile drained with a drain spacing of 15.2 m. The average slope at this site was approximately 1.6%. The site was planted with corn during 1994, soybeans during 1995, and winter wheat during 1995/1996.

This paper focuses on the calibration of RZWQM and long-term simulations of various BMPs in southern Ontario conditions. The detailed description of calibration and validation of RZWQM has been described in McKague (2003).

Calibration of RZWQM An iterative procedure was followed to calibrate the RZWQM. This included calibration of the hydrologic component followed by nutrient and plant growth components. The calibration procedure also followed the recommendations given by model developers and users of RZWQM as outlined by Hanson (2000). The criterion followed for calibration was to minimize the absolute error between the observed and corresponding simulated output. For calibration of the hydrologic component, simulated daily tile flows were compared with observed daily tile flows. Evapotranspiration and runoff estimates as well as watertable depth were also checked and compared with expected values to ensure that a proper water balance was achieved. Calibration of the nutrient component focused on stabilizing the various soil microbial and humus pools. Observed microbial biomass carbon and soil NO_3-N in the top 0.3-m layer of the soil during the growing season were compared with the model output. Crop yield data were used for calibration of the crop growth component of the RZWQM.

The most sensitive inputs for the hydrology component were the Brooks and Corey fitting parameters of bubbling pressure (Ψ_{bp}), pore size distribution index (λ), and saturated hydraulic conductivity (K_s). RZWQM accurately simulated tile drain flow; however, tile drain flow was highly sensitive to Ψ_{bp}, λ , K_s, and moderately sensitive to drainable porosity. Also, the wide range of the measured and calculated values of K_s emphasized the need to include it as a variable in the calibration process.

The sensitivity analysis of the nutrient component of the model focused largely on the effect of macropores on N losses to tile drains. It showed that the fraction of dead end pores had relatively little effect on the N losses in tile drainage water. Also, the model tended to underestimate the amount of soil NO_3-N at the calibration site. The inability of model to handle the spatial and temporal variability of the field processes affected its prediction accuracy. Input variables such as age effect variables, leaf stomatal resistance (L_{sr}), biomass for leaf area index (SLW), and photosynthate to the respiration ratio (R_1) in the crop component affected the simulated crop yield, N uptake, and evapotranspiration rate. The evapotranspiration estimates by RZWQM (468 ± 55 mm) for the calibration site were within an acceptable range for southern Ontario (Dickinson and Diiwu 2000; Rudra et al. 2000). The detailed description of the calibration of RZWQM has been described in McKague (2003).

Figure 1 presents the comparison of the RZWQM calibrated daily tile drainage flow hydrograph with observed tile flow hydrograph for the study site. The calibrated RZWQM seems to perform reasonably well for prediction of tile flow. Over the three-year period (1994-1996), the total simulated tile flow volume was within 5% of the observed volume of tile flow. The timings of the simulated events in most cases matched reasonably well with the observed events; however, the late fall period showed many inconsistencies.

Table 1 shows the comparison of observed available soil moisture content with the RZWQM calibrated estimates of soil moisture in the top 300 mm of soil. These data show that while the estimate of soil moisture was close to observed values, it overestimated soil moisture. Table 1 also shows the comparison of simulated and observed NO_3-N concentration in the 0-300 mm soil zone. For most observations, NO_3-N in the soil profile was underestimated by the model, suggesting a need to revise the ammonification and decomposition rate input variables in the OMNI model. It was particularly poor in estimating mineral N during the early spring period. The simplified approach of winter dynamics used in the RZWQM may be a factor in this case. However, soil biomass was also overestimated in the soil profile (Table 1).

In general the model estimates for soil microbial biomass, soil NO_3-N, and NO_3-N concentrations in tile flow did not tend to have fluctuations similar to the observed data. The pre-calibration results indicated that RZWQM is not a reliable tool in predicting microbial levels in the early months following winter compared to the later part of the growing season. The top layer of the soil profile is likely to be the most difficult zone for predicting microbial population due to variability in the environmental conditions such as soil temperature and soil moisture. However, the model reasonably represented the soil temperature for the field conditions.

The calibrated corn yield (6355 kg/ha) was very close to the observed yield (6360 kg/ha). The N uptake for corn was very close (+1.3%) to the observed values, but the calibrated soybean yield was almost 12% lower than the observed yield. These results gave further confidence in the model's ability to predict yield on the calibration site. The results for hydrology, nutrient,

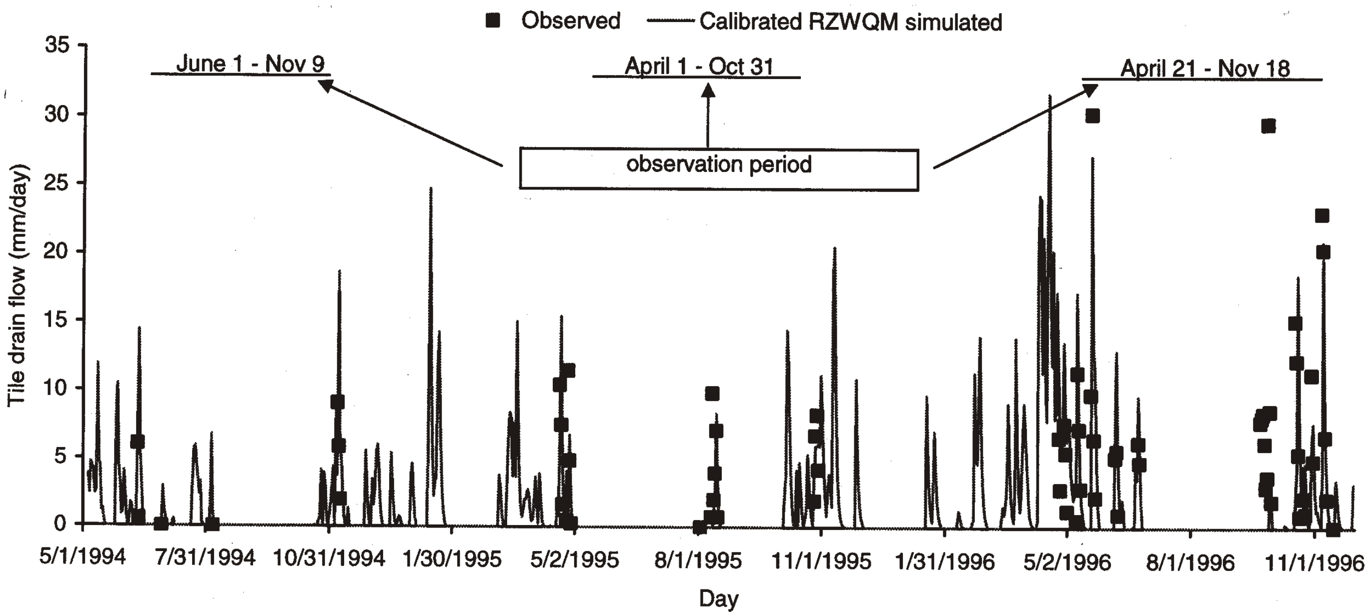

Fig. 1. Comparison of daily RZWQM simulated and observed tile drain flow for the calibration site.

Table 1. Observed and RZWQM simulated soil moisture, soil NO_3-N, and soil biomass for the calibration site.

Date	Soil moisture (% mass) 0 - 300 mm		Soil NO_3-N (ppm) 0 - 300 mm		Soil biomass (mg/kg) 0 - 150 mm	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
May 1994	48.8	63.8	21.6	0.6	728.6	390
June 1994	44.2	62.5	34.1	23.3		
July 1994	45.1	62.7	35.5	17.2		
September 1994					777.1	557
October 1994			22.7		548.3	594
April 1995			30.8	7.5	99.7	659
May 1995			9.2	22.5		
June 1995			8.6	12.1	638.4	597
August 1995			10.1	7.7	298.7	583
October 1995			10.6	8.5	458.5	490
May 1996	50.4	64.5	16.1	0.5	232.0	337
June 1996	46.0	65.5	35.9	78.3		
July 1996	52.0	52.3	31.8	74.9		
August 1996					545.0	409
October 1996					399.0	396
November 1996	51.0	62.0				
Average	48.2	61.9	22.3	21.2	472.5	501.2
Difference (%)	+28.4		-4.9		+6.0	

and crop growth components of RZWQM for the calibration site were used to build the input data set for long-term evaluation of BMPs for southern Ontario.

Definition of reference field To enable an evaluation and comparison of nitrogen fertilization BMPs, a reference field was defined and subsequently RZWQM was applied using appropriate input data (Table 2). The Listowel silt loam soil, selected for modeling, is representative of a hydrologic soil group B. The characteristics and management of the reference field were similar to the field site used for calibration of RZWQM. Table 3 shows a detailed description of the management characteristics at the reference site. The cropping and management practices chosen are common for cash-crops in Ontario.

To address climate variability at the site, the cropping system was modeled continuously for a period of 96 years. Weather data for the London, Ontario weather station, generated by the ClimGen weather generator (Nelson 1996), were used for modeling. The output from 96 years of corn-soybean simulation on the reference site was then used as the "frame of reference" for evaluating selected BMPs. The RZWQM output generated for various BMPs was compared with the reference condition. At this stage, equal weightage was given to the impact of selected BMPs on crop production (economics) and tile drainage nitrate loadings (environmental protection). A detailed description of the N application amounts and timings of various BMPs for long-term simulations using RZWQM is given in Table 4.

RESULTS and DISCUSSION

Evaluation of MERN

In southern Ontario, the nitrogen recommendation for corn in a corn-soybean rotation is 175kg N/ha (OMAFRA 2002b). To assess the year-to-year variability of MERN, twelve N

Table 2. RZWQM input data used to describe the silt loam profile used as the reference soil.

Horizon number	Depth (m)	Texture			OM[α] (%)	BD[β] (Mg/m^3)	Brooks and Corey coefficients		
		Sand (%)	Silt (%)	Clay (%)			Ψ_{bp}[†]	λ[‡]	θ*
1	0.0-0.1	20	60	20	3.7	1.30	29.17	0.207	0.08
2	0.1-0.25	20	60	20	3.3	1.40	11.48	0.118	0.02
3	0.25-0.45	17	58	25	1.2	1.47	12.06	0.112	0.05
4	0.45-0.80	20	55	25	0.7	1.50	12.06	0.112	0.06
5	0.80-1.20	20	55	25	0.4	1.55	12.06	0.112	0.08
6	1.20-2.25	20	55	25	0.3	1.58	12.07	0.112	0.09
7	2.25-3.00	20	55	25	0.2	1.63	12.13	0.075	0.02

[α] Organic matter; [β] Bulk density; [†] Bubbling pressure; [‡] Pore size distribution index; * Residual water content

Table 3. Characteristics of the reference field crop system used as the baseline to evaluate BMPs.

Production system parameter	Baseline condition
Soil profile	Silt loam (hydrologic soil group B)
Tile drainage	Yes, systematic
Crop rotation	1 year corn, 1 year soybean
Tillage system	No-till
N fertilizer form applied	Commercial N
Time fertilizer applied	At planting
Frequency applied	1 time, in year of corn
Amount of fertilizer N applied	OMAFRA* recommended rates for London, Ontario area (175 kg/ha)

*Ontario Ministry of Agriculture and Food

fertilization rates (0, 30, 61, 92, 122, 138, 153, 168, 184, 214, 245, and 275 kg N/ha) were evaluated at the reference field. The RZWQM was used to simulate yearly corn yield and the nitrogen application rate over the 96-year corn-soybean simulation period to develop a set of yield response curves (as shown in Fig. 2) for each year of corn production. The data points represent the annual response and the solid line represents the average trend of corn yield with respect to N application rate over the simulation period. Also shown are the response lines for the minimum and maximum precipitation during the simulation period. These data show that the shape of the yield response curve did not change from year to year and is similar to the shape of the response curve observed in field plot studies; however, there is a shift in the vertical positioning of the curves, which is due to year-to-year variations in climatic characteristics.

The data presented in Fig. 2 were also used to calculate long-term MERN, assuming a nitrogen-to-corn price ratio of 5. The shape of the yield response curve was represented by a quadratic model and the quadratic plateau model. The quadratic model is the basis for current Ontario N recommendations for corn (Beauchamp et al. 1987). However, there is general feeling that the quadratic plateau model gives improved and lower value for the MERN for corn (Bullock and Bullock 1994; Hayes 2001). The average value of MERN estimated from the data given in Fig. 2 for the quadratic model and quadratic plateau model was 184 and 165 kg N/ha, respectively. A paired t-test indicated no significant difference in these values at 95% level of probability. Therefore, the current N recommendation for Ontario (175 kg N /ha) lies between these two values and looks appropriate.

Figure 3 shows the variation in annual MERN and corn yield. Though the average long-term simulated MERN matches very well with current Ontario N fertilization recommendations, these data also show a significant yearly variation in the value of MERN. This may be due to the variations in annual precipitation. Also, there are two outliers for the years 2018 and 2066. The RZWQM-simulated yield response curves suggest lower corn yield during wet years as compared to the dry years for this region. Corn yield and annual precipitation data for the Middlesex County support these findings (Table 5). With the exception of 2001, these data indicate that lower yield tends to occur during wet years. The lower yield during 2001 was due to extremely dry weather during peak growth months of June and July. This also confirms that the RZWQM predictions are realistic and also reflect the effect of regional climatic characteristics on corn yield. Another advantage of using the modeling approach to develop yield response curves is that it also gives the information on the corresponding environmental impact of N fertilization rates, which are not measured in typical fertilizer response field trials.

Figure 4 shows the predicted average flow-weighted annual NO_3-N concentrations in the subsurface drainage flows corresponding to the yield response curves in Fig. 2. These data indicate that year-to-year variability in the weather pattern also has a significant influence on the environmental impact of nitrogen application at the MERN level. The lowest environmental impact occurred during dry years while the highest impact occurred during wet years. There seems to be some inconsistency between the simulated results and field

Table 4. Nitrogen application rates and timings for various BMPs simulated by RZWQM.

BMPs	Rate and timing
Planting time N application	184 kg/ha
Split N application	10 kg/ha at planting + 96 kg/ha on May 30 + 78 kg/ha on June 20
Side dress N application	10 kg/ha at planting + remainder on June 15 at six-leaf stage

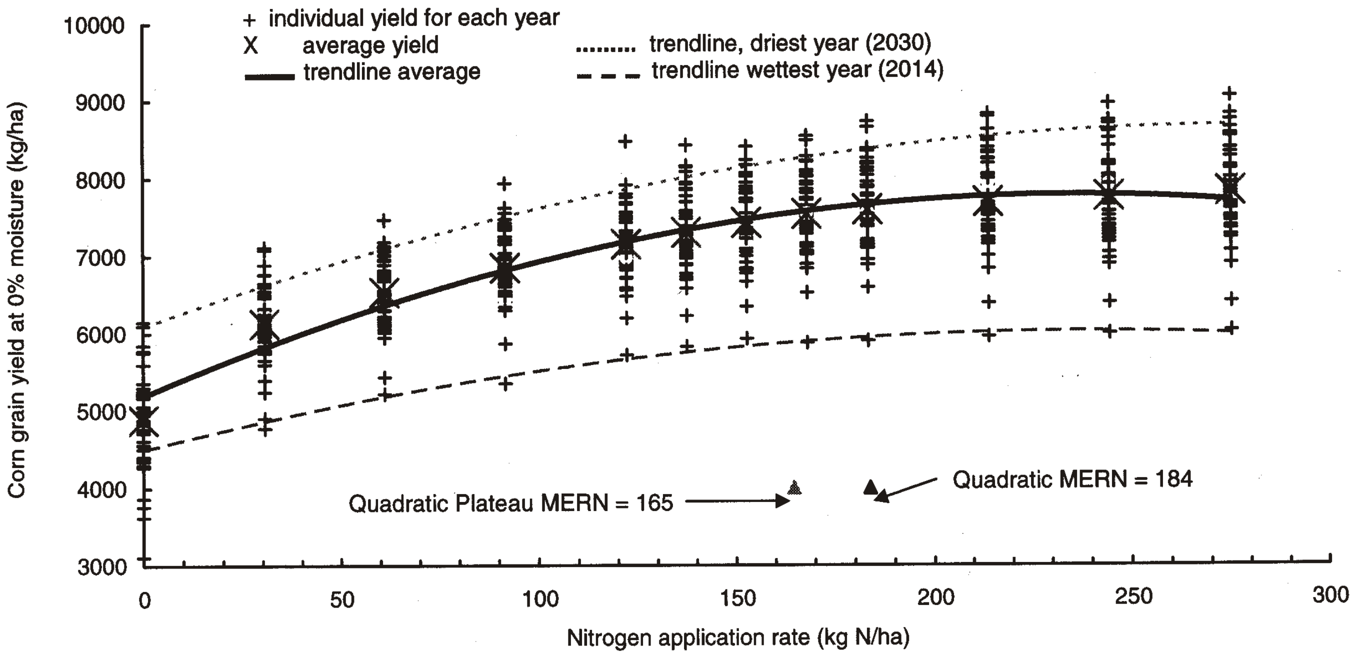

Fig. 2. Corn yield response to N fertilization simulated by RZWQM.

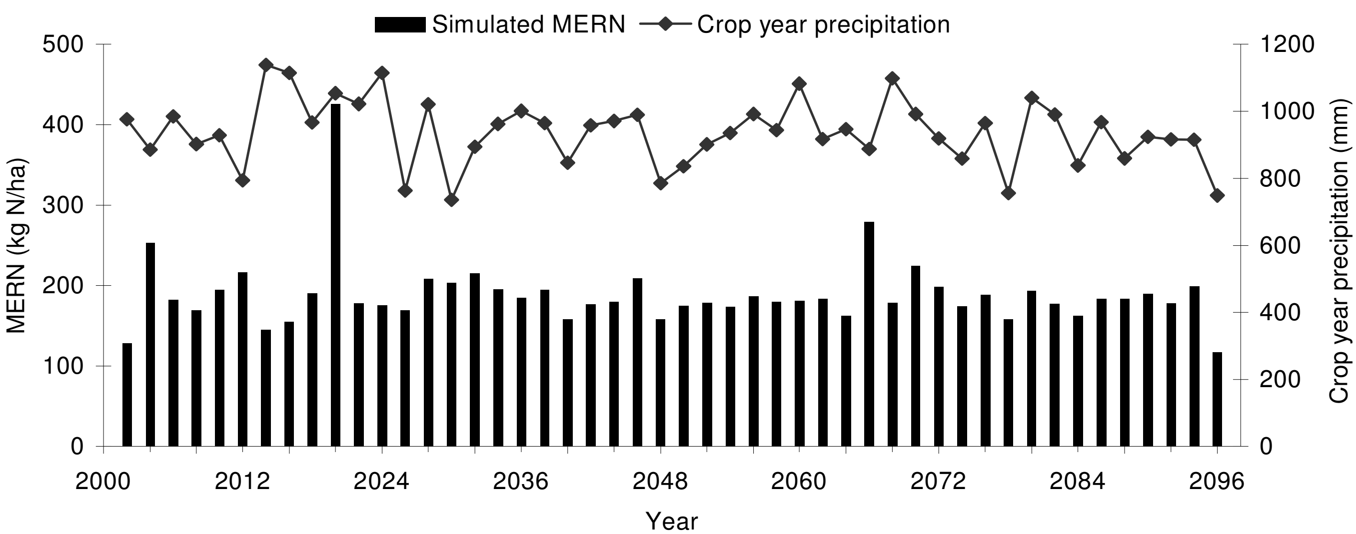

Fig. 3. RZWQM-simulated annual fluctuations in MERN.

Table 5. Corn grain yields and annual precipitation amounts for the Middlesex County.

Year	Average grain corn yield (kg/ha at 15.5% moisture)	Precipitation (mm)	Annual precipitation relative to long term normal*
1996	7230	1112.0	Wet†
1997	7904	969.0	Wet
1998	8970	765.4	Dry‡
1999	8908	786.1	Dry
2000	7339	1083.4	Wet
2001	6336	861.2	Dry

* 30-year (1971-2000) average precipitation = 927.6 mm
† Above average precipitation
‡ Below average precipitation

observations. In dry years, total NO_3-N loads in the tile outflows are expected to be significantly lower; a higher average NO_3-N concentration and small outflows during a dry year seems more plausible.

The modeling approach also used a scenario to determine the environmental benefits of MERN for future years. Such a scenario is only possible with a knowledge of future climate, which was obtained by using climate generators. For such analysis, annual NO_3-N losses in the tile flow predicted by RZWQM for MERN rate for corn was compared with the annual nitrate losses in the

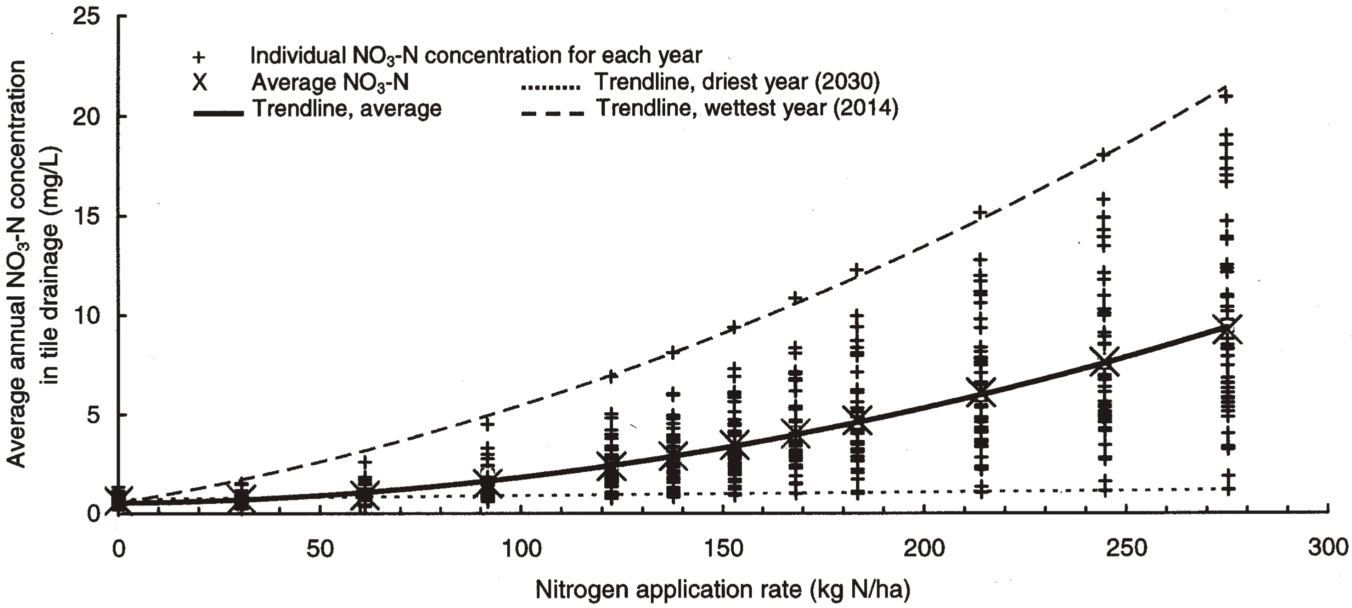

Fig. 4. RZWQM-simulated annual tile drainage NO_3-N concentration response to N fertilization as influenced by climate variability.

tile outflow by applying the long-term average MERN of 184 kg/ha per year. For the reference site, there was no significant difference in the average annual tile NO_3-N losses (44.2 versus 44.3 kg/ha) over 96 years of simulation period. This approach did not consider the potential differences in residual N resulting from the application of different nitrogen rates between years. Nevertheless, the negligible difference suggests that efforts to improve N use efficiency by fine-tuning our ability to accurately predict the weather in a growing season may have little effect on reducing environmental impacts. It could, however, have significant economic production benefits.

The data in Fig. 4 also show that nitrate concentrations increase significantly with increase in nitrogen application rate. For this site, exceeding the drinking water standard of 10 mg/L NO_3-N is far more likely to occur at rates above the MERN. The proposed Canadian interim surface water guideline of approximately 3 mg/L NO_3-N would only be achievable with significant reduction in fertilization rates, which would also result in significant reduction in corn yield and farm income.

The results obtained from the output of RZWQM were also used to identify the season when NO_3-N losses are most likely to occur (Table 6). From the 96 years of simulation results for the reference field it appears that about 56% of the NO_3-N loads occur during the winter and early spring (December 15 to April 14). It was due to more subsurface drainage flow (about 35%) during the late spring and early summer period from April 15 to June 30. These results correspond well with the observations of Tan et al. (2002). They reported that in southwestern Ontario approximately 65% of the cumulative drainage and surface runoff occur during the non-growing season (November to March). These results suggest that minimizing the amount of available NO_3-N in the soil over the winter and spring seasons could help reduce the risk of NO_3-N losses to subsurface drainage flows.

Side-dress N application

Side-dress application of N (10 kg/ha at planting plus remainder on June 15 at six leaf stage) is often the recommended practice to improve N use efficiency. In the side dress application, nitrogen is placed in the soil root zone closer to the plant at the time when it will be taken up by the crop. In this N application approach, there is less opportunity for nitrogen to be lost through leaching or through denitrification because of less

Table 6. Summary of average seasonal tile drainage nitrate loads from 96 years of RZWQM simulation - silt loam reference site.

Measurement	Nitrate load in tile drains (kg)				
	Spring (April 15 - June 30)	Summer (July 1 - Sept 14)	Fall (Sept 15 - Dec 14)	Winter (Dec 15 - April 14)	Crop year
Average	12.95	0.35	2.95	20.97	37.22
Minimum	1.96	0	0	0	7.22
Maximum	60.04	11.15	39.36	60.54	114.74
SD	8.42	1.40	6.95	13.54	17.75
Percent of annual	34.8	0.9	8.0	56.3	100

exposure to weather conditions. This BMP was evaluated on the reference field site by using RZWQM to simulate 10 kg N/ha application at corn planting time and the remainder, required to meet production recommendations, applied on June 15. The comparison of the output from this fertilization practice with the reference practice (all at planting) revealed that minimal long-term benefits are achievable from side-dress application. While reductions in environmental (NO_3-N) losses during spring were significant as a result of side-dressing of nitrogen, more residual soil nitrogen from the same side-dress application was lost to the environment the following winter and spring. Over the simulation period, the long-term reduction in nitrate loss achieved with side-dress application was only 1.3%. This practice resulted in a 5.8% reduction in the corn yield, which was significant at the 5% probability level.

Split N applications

The RZWQM was also used to analyze the application of nitrogen fertilizer closer to the time of peak demand by corn. This scenario was evaluated by applying 10 kg N/ha at planting, 96 kg N/ha three weeks later (May 30), and 78 kg N/ha another three weeks later on June 20. The simulated results suggest 11.3% reduction in NO_3-N loads in the tile outflow and 7.6% reduction in corn yield (8306 kg/ha) by split application of nitrogen in comparison to crop yield for planting time single application (8990 kg/ha). The reduction in yield was significant at the 5% probability level.

Pre-side-dress N test (PSNT)

Ontario has a calibrated PSNT for corn production. Soil samples, taken at 0.3 m depth and analyzed for NO_3-N concentrations when corn is at the 3 to 5 leaf stage, are used to estimate the additional fertilizer N required for optimum yield. For a nitrogen-to-corn price ratio of 5, the recommended additional N to be applied was calculated by using Eq. 1.

$$N_{rec} = 224.13 - 9.706 N_{oil} \quad (1)$$

where:

N_{rec} = PSNT recommendation for additional fertilizer N (kg/ha), and

N_{soil} = soil nitrate concentration in top 0.3 m of soil (mg/L).

To evaluate the effect of this BMP, the RZWQM output files were queried on June 7 of each year of corn production to determine the predicted soil nitrate concentration in the top 0.3-m layer. Until June 7 no fertilizer was applied. The recommended additional fertilizer N to be applied was estimated by using Eq. 1. The average value of PSNT recommendation for the reference field was 172.5 kg N/ha. This practice resulted in 6% reduction in the average MERN value estimated over the simulation period. There was no significant difference in yield.

Reduced N applications through crop rotation

The effect of change in crop rotation (from corn-soybean to corn-soybean-soybean) on NO_3-N loss to the tile drainage water was also investigated using RZWQM. This change in rotation on the reference field resulted in a 33% reduction in the amount of N fertilizer application and 19.1% reduction in the average annual NO_3-N concentration in the tile outflow over the 96 years of simulation period. The model could not identify any impact on corn yield because it does not have the capability to model the possible change in diseases or pest pressures resulting from change in management practices.

CONCLUSIONS

The following conclusion can be drawn from the results of this study:

- The long-term average MERN calculated by the RZWQM is similar to the current crop production recommendations for corn in the southwestern Ontario. Application of fertilizer at MERN rate does not always meet drinking water standards (10 mg/L) for NO_3-N concentrations in tile outflow. The proposed Canadian surface water quality guidelines for NO_3-N are often difficult to achieve under economic production practices. The average annual NO_3-N concentrations in tile outflow often fluctuate significantly from year-to-year due to annual variations in the climatic conditions and also depend upon the N fertilization rates.
- Minimizing the amount of available NO_3-N in the soil profile over the winter and spring period and crop rotation system can reduce the risk of nitrate losses. The results of this study also indicate that the highest loss (56%) of NO_3-N is most likely to occur during the winter and early spring period (December 15 to April 14) followed by 35% during the spring and early summer period (April 15 to June 30) and the remaining (9%) during the fall period.
- Delaying the N application until side-dress time results non-significant reduction in NO_3-N losses to subsurface drainage water and significant decrease in corn yield relative to single application at planting time. Split application of N fertilizer also results in a significant decrease in the average annual NO_3-N concentration in tile outflows and a marginal decrease in crop yield relative to single application at planting time.
- The PSNT can detect early-season weather impacts on inherent soil nitrogen availability. Therefore, PSNT can result in a moderate decline in N fertilizer with non-significant effect on crop yield.
- The introduction of legumes into the crop rotation results in significant reduction in N application and a significant reduction in NO_3-N loads in the tile outflows with no significant decline in crop yield.

Overall, this simulation study concludes that the RZWQM is an effective tool for calculating subsurface drainage water quality and crop yield. These long-term simulation results also help evaluate the economic and environmental effects of BMPs on crop yields and subsurface drainage water quality in southern Ontario.

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