Watertable management for reducing nitrate accumulation in a soil profile under corn production

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Elmi, A.A., Gordon, R., Madramootoo, C. and Madani, A. 2005. **Watertable management for reducing nitrate accumulation in a soil profile under corn production**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **47**: 1.23 - 1.28. Nitrogen (N) fertilization is an important component of modern agricultural production. However, N (mainly in the form of nitrate-N; NO_3^--N) becomes problematic when it moves from agricultural soils into surface water bodies or leaches into groundwater systems. Field trials were conducted on long-term experimental plots to investigate the combined effects of watertable management (WTM) and N fertilization rate on NO_3^--N concentration in the soil profile and on corn (*Zea mays* L.) yield. There were two watertable treatments: free drainage (FD) with open drains at a 1.0 m depth from the soil surface and subirrigation (SI) with a target watertable depth of 0.6 m below the soil surface, factorially combined with two N fertilizer rates: 120 kg N/ha (N_{120}) and 200 kg N/ha (N_{200}). Treatments were laid out in a split-plot fashion. This paper reports on soil NO_3^--N and corn yield in 1999 and 2000. Corn yield was unaffected by WTM and N rate treatments in both years. Compared to FD, SI reduced NO_3^--Nconcentration in the soil profile (0-0.75 m) by up to 50% averaged over the two N rates. These findings suggest that SI can be used as a means of reducing NO_3^--N without compromising crop yields. **Keywords:** corn, concentration, nitrate, pollution, yield.

La fertilisation azotée (N) est un élément important de la production agricole moderne. Cependant, l'azote (principalement sous forme de nitrate-N : NO_3^--N) devient un problème lorsqu'il se déplace des sols agricoles aux eaux de surface ou qu'il migre dans la nappe phréatique. Des essais à long terme ont été réalisés sur des parcelles expérimentales pour étudier l'effet combiné de la gestion de la nappe phréatique (GNP) et des taux de fertilisation sur la concentration en NO_3^--N dans le profil de sol et sur les rendements en maïs (*Zea mays* L.). Deux types de gestion de la nappe phréatique ont été utilisés : drainage libre (DL) avec drains ouverts placés à 1,0 m sous la surface du sol et irrigation souterraine (IS) avec une profondeur cible de 0,6 m sous la surface du sol pour la nappe phréatique avec une combinaison factorielle de taux de fertilisation N : 120 kg N/ha (N_{120}) et 200 kg N/ha (N_{200}). Le design expérimental était en split-plot. Cet article présente les résultats sur la concentration en NO_3^--N et le rendement en maïs en 1999 et 2000. Les rendements en maïs n'ont pas été affectés par la GNP et les différents taux de N pour les deux années. Comparé au DL, IS a réduit la concentration en NO_3^-N dans le profil de sol (0 - 0,75 m) jusqu'à 50% en moyenne pour les deux taux de fertilisation azotée. Ces résultats suggèrent que la IS peut être utilisée comme moyen de réduire NO_3^--N sans compromettre le rendement des récoltes. **Mots clés**: maïs, concentration, nitrate, pollution, rendement.

INTRODUCTION

Food production has kept pace with population growth over the past decades largely because of the increased use of fertilizers and pesticides and the development of more efficient irrigation systems as well as improved cultivars. An FAO study (FAO 2000) indicates that the nitrogen (N) fertilizer consumption in the world is expected to increase dramatically, with corn (*Zea mays* L.) emerging to be the foremost user. Although the benefits of N for food production are well recognized, increases in N fertilizer and water use however, can result in off-site negative environmental consequences. Several studies have shown that soil nitrate-N (NO_3^--N) which remains in the unsaturated zone of the soil profile at the end of the growing season is the most common contaminant of surface waters and shallow groundwater because NO_3^--N rapidly moves through the soil profile (Randall and Mulla 2001; Patni et al. 1998).

When translocated to a lower depth of soil profile, NO_3^--N becomes unavailable for plant uptake and a danger to the quality of the underlying water systems. Pollution of groundwater by NO_3^--N leaching can lead to the loss of safe drinking water, since high levels of NO_3^--N in drinking water may cause methemoglobinemia (also known as Blue baby syndrome) (Comly 1945). Furthermore, discharge of NO_3^--N into surface waters via tile drainage systems can lead to enhanced eutrophication in aquatic ecosystems. Hatfield et al. (1999) suggested that approximately 95% of NO_3^--N passing through the root zone is intercepted by a tile drain system and moves eventually as discharge into surface waters. The ecological impacts of eutrophication can be dramatic since decomposition of the excessive biomass leads to depletion of oxygen. Strategies to reduce NO_3^--N pollution should, therefore, seek to prevent accumulation of NO_3^--N in the soil profile.

Watertable management (WTM) is a practice with demonstrated positive effects on water quality by reducing NO_3^--N concentrations in the soil profile and on crop performance (Elmi et al. 2002a; Cooper et al. 1999; Drury et al. 1997; Kalita and Kanwar 1993). Watertable management consists of two main alternatives: controlled drainage (CD) and subirrigation (SI). Under CD, water is prevented from leaving the drain outlet by means of raising the drainage outlet. No supplemental water, other than rainfall, is added to the system. Subirrigation is similar to the CD system, except that supplemental water is pumped into the system to maintain the watertable at a target depth. Controlled drainage-subirrigation (CD-SI) reduces NO_3^--N pollution problems either by regulating the volume of drain discharge (Kliewer and Gilliam 1995; Wright et al. 1992; Gilliam and Skaggs 1986) and/or by creating anaerobic conditions which enhance denitrification (Elmi et al. 2002b, 2000; Jacinthe et al. 2000).

Although a number of agricultural mitigative measures have been implemented to reduce the amount of excessive NO_3^--N in the soil profile after harvest, NO_3^--N losses to aquatic ecosystems continue to be a ubiquitous pollutant. The work presented here is part of a long-term study initiated in 1992 to evaluate WTM system's impacts on nutrient losses from a corn agro-ecosystem in southwestern Quebec, Canada. Specific objectives of this study were to investigate the long-term impacts of WTM and N fertilization rate on corn yield and evaluate WTM effectiveness in lowering NO_3^--N in the soil profile.

MATERIALS and METHODS

Field history and management

The research was conducted on a 4.2-ha privately-owned field located at St-Emmanuel near Côteau-du-Lac, Quebec (74^o 11' 15'' N, 45^o 21' 0'' W), about 30 km southwest of the Macdonald Campus of McGill University, Montreal, Quebec. Site design and instrumentation is detailed in Tait et al. (1995). The soil, a Soulanges fine sandy loam (fine silty, mixed, non-acid, frigid *Humaquept*), is of sedimentary origin. Surface topography is generally flat with an average slope of less than 0.5%. The fine sandy loam soil (0-0.25 m) is underlain by layers of sandy clay loam (0.25-0.55 m) and clay (0.55-1.0 m), and the clay layer impedes the natural drainage. Experimental plots were under conventional tillage (i.e., moldboard plow to 0.20 m in the fall and disk in the spring), the common practice in the region. The site had been a pasture prior to 1992, when it was converted to monocrop corn and corn intercropped with annual Italian ryegrass (*Bamultra*) production. Annual Italian ryegrass was sown between corn rows of intercrop treatment plots. Results of soil NO_3^--N concentrations from these two cropping systems (monocroped vs intercroped) research are reported by Zhou et al. (1997). From 1995 and onward, the site had been under monoculture corn.

Field management and experimental design

The field was planted with corn (Pioneer hybrid 3905) at a density of 75,000 seeds/ha at a 0.75 m interrow spacing. A John Deere 700 series planter equipped with 50-mm fluted coulters completed planting on 4 May 1999 and 23 May 2000. Potassium (muriate of potash, 0-0-60; NPK) was broadcast at a rate of 90 kg K_2O/ha roughly one week before planting. To control weeds, 1.5 kg a.i. /ha atrazine, 0.32 kg a.i./ha dicamba, 0.32 kg a.i./ha bromoxynil, and 1.92 kg a.i./ha metolachlor were applied to the field on 28 May 1999 and 23 June 2000.

Field layout and treatment arrangements are detailed elsewhere (Elmi et al. 2000, 2002b). Briefly, there were two watertable management treatments: free drainage (FD) with open drains 1 m below the soil surface and SI with a target watertable of 0.6 m below the soil surface and two fertilizer rates: 120 kg N/ha (N_{120}) and 200 kg N/ha (N_{200}). Nitrogen fertilizer was applied in a split dose: 23 kg N/ha banded as diammonium phosphate (18-46-0; NPK) at planting and 97 kg N/ha or 177 kg N/ha broadcast as ammonium nitrate (34-0-0; NPK) one month after planting (10 June 1999 and 20 June 2000), resulting in rates of 120 kg N/ha (N_{120}) and 200 kg N/ha (N_{200}), respectively.

Treatments were laid out in a split-plot design with WTM treatment as the main plot and N fertilization as the subplot. The WTM treatments were established in 30 m wide and 75 m long plots, and each main plot was split into two 15 m x 75 m subplots. Fertilizer treatments were assigned randomly to the subplots. Each treatment was replicated in three blocks. Blocks were separated by a 30-m wide strip of undrained land. To minimize seepage and chemical flow between plots, 0.6 mm polyethylene sheeting was installed to a depth of 1.5 m between plots (Tait et al. 1995). In addition, adjacent to each main plot (WTM treatment) were buffer plots with 75-mm diameter subsurface drain pipes installed at 1.0 m depth with a slope of 0.3%.

Subirrigation treatment was imposed two weeks after planting and maintained until crop maturity in late September. Well water with no detectable NO_3^- -N was continuously pumped into the field to balance crop use and evaporative losses. Due to deep seepage it was difficult to maintain watertables at the desired depth. Following heavy rainfall events, pumping was stopped in SI plots and excess water drained until a 0.6 m watertable depth was achieved in the field. To monitor watertable fluctuations, three observation wells, perforated 12-mm diameter polyethylene pipes wrapped with geotextile sleeves (Zodiac, London, ON), were installed diagonally in each treatment or buffer plot to a depth of about 1.4 m. The watertable depth was averaged for each plot. Watertable depths were measured once or twice a week during the growing season by inserting a sonic water sensor mounted on a graduated rod. Drains were opened 17 September in 1999 and 25 September in 2000 to facilitate trafficability for harvesting. Rainfall and air temperature data were obtained from an Environment Canada weather station situated 500 m from the experimental site.

Soil sampling and analysis

Soil samples (three samples per plot) for NO_3^- -N analysis were taken prior to planting in the spring (April or early May) and shortly after harvest in the fall (October) from 0-0.25 m, 0.25-0.50 m, and 0.50-0.75 m depth increments for each year using a hand-held auger sampling probe. Soil samples were promptly frozen (-4°C) after collection and kept for 1-3 weeks until they were analyzed for NO_3^--N content. Samples were then thoroughly mixed and moist subsamples of 10 g were shaken with 100 mL of 1 M KCl for 60 min. The soil suspensions were filtered through Whatman #5 filter papers. Nitrate-N was quantified using a Lachat flow injection autoanalyzer (Lachat Quickchem, Milwaukee, WI) according to Keeney and Nelson (1982). The detection limit was 0.05 mg/L.

Grain corn sampling

Corn grain yield was determined by hand harvesting individual ears from a subplot consisting of three randomly selected rows (5 m long) in each plot. Grain yield was reported on a dry-weight basis. After harvest, the field was plowed incorporating all corn stover (leaves plus stalks) into the soil.

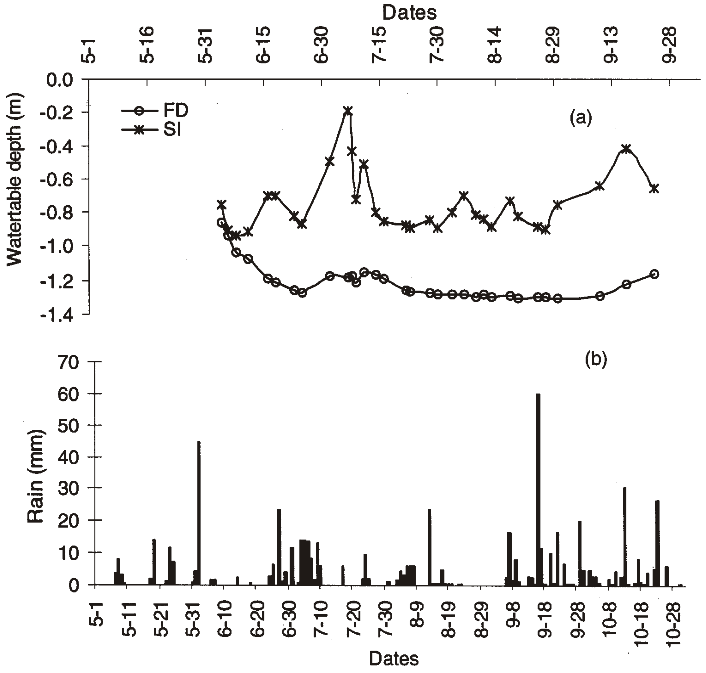

Fig. 1. Watertable fluctuations (a) and daily precipitation (b) during 1999 growing season.

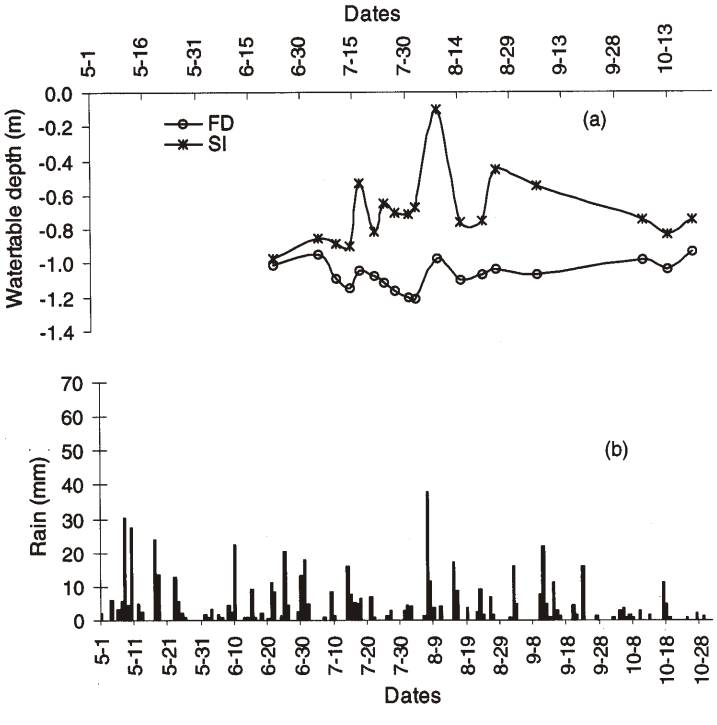

Fig. 2. Watertable fluctuations (a) and daily precipitation (b) during 2000 growing season.

Statistical analysis

Data were analysed as a split plot with watertable being the main plot and fertilizer N treatments as sub-plot. When a main plot effect was significant without any interaction, Fisher's F-test statistic was used to determine statistical significance within each main plot treatment. Unless otherwise noted, statistical significance is reported at the 5% probability level. All statistical analyses were conducted using the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS 1999).

RESULTS and DISCUSSION

Meteorological data and watertable fluctuations

Watertable levels fluctuated throughout the growing seasons, responding primarily to rainfall events (Figs. 1-2). The 1999 cropping season was characterized by a dry summer (Fig. 1b). While total seasonal (May-October) rainfall (589.4 mm) was 13% higher than normal, May and August were 23 and 35% lower than normal, respectively. The first week of July, just three weeks after the second N application, had frequent rainfall events resulting in the shallowest watertable depth (Fig. 1a) of the growing season. For much of 1999, the watertable in FD plots remained deeper than 1.0 m, whereas in SI plots the watertable was on average 0.8 m below the soil surface. A single rainfall event on 16 September provided 29% of the total growing season rainfall (Fig. 1b) resulting in a watertable shallower than the design depth (0.6 m) (Fig. 1a). Rainfall during the 1999 cropping season totaled 589 mm, with nearly half (276 mm) falling in September and October.

During the 2000 growing season, total rainfall (583 mm) was about 12% higher than normal. May was the wettest month, accounting for 25% of seasonal rainfall with October being the driest month, accounting for less than 5% of total rainfall (Fig. 2b). The shallowest WTD under SI (Fig. 2a) corresponded to a rainfall event that delivered 39 mm on 7 August (Fig. 2b). For SI systems to be successful, watertable depth must be high enough to permit capillary rise into the root zone and low enough to ensure adequate soil aeration.

Effects of watertable and N fertilization rate on corn yield

Corn yields were not significantly ($p > 0.05$) affected by treatments in either year (Table 1). Subirrigation is expected to be more beneficial than conventional drainage during drier crop seasons as it supplements rainfall to meet crop evapotranspiration demand. Growing conditions (rainfall and temperature) were similar to normal in both 1999 and 2000. From the same site, Elmi et al. (2002b) reported a significantly higher yield under SI in 1997, which was drier than normal. Similarly, Cooper et al. (1999) recorded a significant yield increase with a SI treatment in 1991, a very dry year, whereas wet growing conditions of 1992 resulted in conventional drainage yields not differing from those obtained under SI. Skaggs et al. (1999) suggested that raising the watertable generally increases evapotranspiration and, hence, yield. Tan et al. (1996) made similar observations and concluded that corn grain yields on a sandy loam soil were less with a watertable depth of 0.8 m as compared to 0.6 m because stomatal conductance and transpiration rate were reduced by water stress. Doty (1980) found that the optimum watertable depth for corn in sands or sandy loam to be 0.76-0.89 m.

Table 1. Yield of corn (Mg/ha) in relation to watertable management and nitrogen fertilization rate.

Year	Watertable treatment		Nitrogen fertilizer treatment	
	Free drainage	Subirrigation	120 kg N/ha	200 kg N/ha
1999	8.5	8.4	8.3	8.6
2000	7.3	6.7	6.8	7.0

Corn yield was not responsive to N fertilization rate (Table 1). This indicates that 120 kg N/ha was sufficient to optimize crop yield under conditions of no drought stress. The farmer applied manure (cattle slurry) in spring 1998 at a rate of approximately 20 Mg/ha (wet mass) prior to the initiation of this experiment. Eghball (2000) estimated that 40, 20, 10, and 5% of the applied manure-N would be plant available in the first, second, third, and fourth years after application, respectively, while N from inorganic fertilizers is assumed to be 100% plant available during the year of application. Manures are routinely applied to agricultural lands near livestock operations to dispose of manure, because transportation of manure to a great distance (>30 km) is prohibitively expensive. It is to be expected that this practice may even intensify in the near future as other routes of manure disposal become increasingly restricted due to more stringent regulatory measures. In a sustainable farming system, manure-N has to be given the same importance as chemical fertilizers; manure should be viewed as a resource rather a waste to be disposed. With no information available regarding how much N was available from the manure, we recognize that this could have masked the effect of N fertilizer rate on the yield.

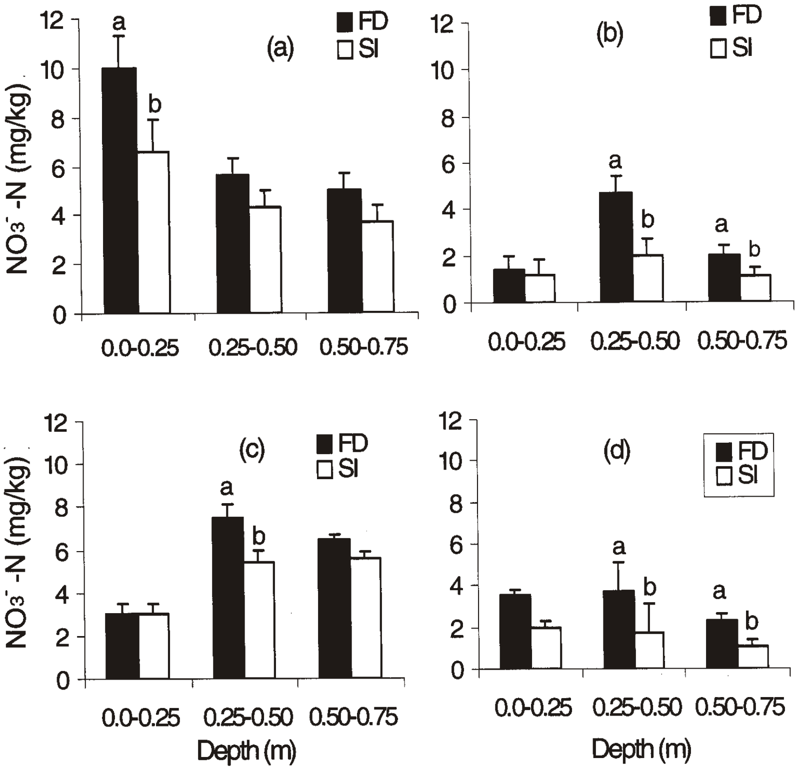

Fig. 3. NO_3^--N concentrations (mg/kg dry soil) in the soil profile under free drainage (FD) and subirrigation (SI) treatments in (a) spring 1999, (b) fall 1999, (c) spring 2000, (d) fall 2000. Charts within same depth followed by different letters are significantly ($p < 0.05$) different. Vertical bars represent standard error of the mean ($n = 9$).

Yields were lower in 2000 than 1999 (Table 1). This is likely due to the late planting date of the field because of weather conditions and some technical difficulties.

Watertable effects on NO_3^--N levels in the soil profile

Free drainage plots accumulated significantly greater NO_3^--N levels between 0.25 and 0.75 m in the soil profile (Fig. 3). In 1999, the difference between FD and SI was also significant at the uppermost layer in the spring (Fig. 3a), whereas in 2000 the difference was significant at the intermediate depth (Fig. 3c). These findings suggest that the effects of WTM treatments were more pronounced in the fall than spring at the deeper depths of the soil profile. This may be because sampling in the spring was done seven months after SI was switched into FD, and the carryover effect of SI treatment was minimal, whereas in the fall, sampling was done immediately after SI was switched into FD mode. Greater NO_3^--N levels at the uppermost soil layer (0-0.25 m) in the spring of 1999 (Fig. 3a) than 2000 (Fig. 3c) may be due to the slow and continuous mineralization of manure applied in 1998 spring. As noted previously, Eghball (2000) suggested that a major portion of the manure applied in the spring was mineralized during the subsequent summer.

In general, there was a trend for NO_3^--N concentrations in the soil to decrease with depth under both WTM treatments, except spring 2000 (Fig. 3c). Heavy rains in the fall of 1999 (Fig. 1b) might have caused NO_3^--N leaching with percolation water. In coarse-textured soils such as at the study site, NO_3^--N can be leached easily below the crop rooting zone, particularly after harvest. This may explain the sharp increase of soil NO_3^--N concentrations with depth in the spring 2000 (Fig. 3c), following the excessively wet fall of 1999.

In spring, when evapotranspiration is low and precipitation and snow melt exceed the water holding capacity of the soil, residual NO_3^--N can leach beyond the crop root zone and, consequently, contaminate surface water resources via subsurface drains or groundwater with percolating water. Patni et al. (1998) estimated that approximately 70% of NO_3^--N leaching occurs from fall to spring (October through April). Keeney and DeLuca (1993) found that NO_3^--N concentrations in the Des Moines river in Iowa, USA were above 10 mg/L for about 14 days per year, mainly in the spring. Drury et al. (1996) reported that up to 88 to 95% of the NO_3^--N loss to subsurface drainage occurred during the noncrop period (November through April). All these observations indicate that NO_3^--N leaching in early spring appears to account for the majority of NO_3^--N loading losses to the subsurface drains which subsequently discharged into surface waters. Implications of these findings are that emphasis should be placed on management strategies that limit the accumulation of NO_3^- in the soil profile during the non-growing season, such as winter cover crops, when plant uptake is minimal and the potential for leaching is highest. Winter cover crops both conserve NO_3^--N within the system that might otherwise be leached below the root zone during winter (Lord et al. 1999) and also protect the fields from surface erosion and increase organic matter content.

Averaged across all depths, reduction of total soil NO_3^--N under SI compared to FD ranged from 2 to 29% in the spring, and 36 to 50% in the fall. Nitrate-N reductions of 30 to 60%, resulting from controlled drainage/subirrigation, have been reported in several studies. For example, Fogiel and Belcher (1991) found that controlled drainage-subirrigation reduced NO_3^--N loading through drainage by 25 to 59% over a two-year period compared with conventional drainage. Gilliam and Skaggs (1986) predicted a 32% decrease in NO_3^- losses due to controlled drainage relative to conventional drainage systems. Jacinthe et al. (1999) reported 24 to 43% reduction in NO_3^- leaching using WTM techniques. Further reductions could be achieved if controlled drainage is kept operational during the early spring, when NO_3^--N losses are most severe (Patni et al.1998; Keeney and DeLuca 1993) and drainage is not needed to optimize crop production. This practice, however, may interfere with tillage operations in early spring. Operation of controlled drains might enhance denitrification and reduce excess NO_3^--N in the soil-water system in early spring, if temperatures are warm enough.

In a lysimeter study, Kalita and Kanwar (1993) found that shallow watertable depths of 0.3 to 0.6 m reduced NO_3^--N concentrations in groundwater to levels below 10 mg NO_3^- -N/L. They postulated that these lower NO_3^--N levels were due to enhanced denitrification resulting from saturated conditions in upper soil layers (0-0.15 m) where the organic matter is greatest. In a previous study at the same field site, Elmi et al. (2002b, 2000) found lower soil NO_3^--N concentrations under SI than FD with no significant differences in drainage outflow volume between SI and FD treatment. Consequently, they concluded that greater denitrification rates in SI than in FD was the key NO_3^--N removal mechanism.

Biological denitrification is also considered as a major source of atmospheric N_2O. The question arises then if WTM technique is a solution to protecting water quality but increasing N_2O emissions (i.e. trading off one environmental problem by another). This concern has emphasized the need for information about the proportion of denitrification gaseous end-products, namely N_2O vs N_2, entering the atmosphere. This topic is discussed in detail in a separate paper (Elmi et al. 2005).

Effects of N fertilizer rate on NO_3^- -N in the soil profile

Nitrogen fertilizer rate [120 kg N/ha (N_{120}) vs 200 kg N/ha (N_{200})] had no significant effect on soil NO_3^--N concentrations at any soil depth (data not shown). This general lack of significant treatment (N_{120} vs N_{200}) effects or even consistent trends suggests that limiting N fertilization alone might not be sufficient strategy to overcome the problem of NO_3^--N loading in the soil-water system, as other sources may contribute to the pool of N in the soil. The first evidence of NO_3^--N movement below the root zone for cultivated soils receiving no mineral N fertilizer or manure was presented in the early 1900s (Buckman 1910). More recently, Sainju et al. (1998) reported that even with no fertilization, significant concentrations of residual NO_3^--N accumulated beyond the root zone because of continued mineralization from soil and crop residues retained on the soil surface. This contribution of N from organic residue is relevant in this study given the fact that manure was applied to the whole site, including our experimental plots, just one year before the initiation of this study. We recognize that this might have obscured the effects of N on NO_3^--N concentrations in the soil profile to be statistically significant. Similar to our findings, Cambardella et al. (1999) found little relationship between N fertilizer rate and NO_3^--N removal in tile drainage.They concluded that although NO_3^--N loss in drain discharge tended to increase with N fertilization rate, N mineralized from soil organic matter and/or manure accounted for a significant portion of the N leached from soil or used by crops.

CONCLUSIONS

This study was undertaken to investigate combined effects of watertable and N fertilization treatments on NO_3^--N concentrations in the soil profile and corn yield. Averaged across all depths and N treatments, soil NO_3^--N concentrations were lowered under SI compared to FD (2 to 29% in the spring and 36 to 50% in the fall). These findings support the idea that the adoption of WTM practices may provide a practicable means for enhanced removal of NO_3^--N from soil-water system and, therefore, control migration and entry of NO_3^--N into surface- and groundwater resources. We conclude that a combination of water and N management is more effective on reducing NO_3^--N accumulation than either approach alone.

Similar yields were obtained with SI and FD in 1999 and 2000. Corn yield was not responsive to N fertilization rate. We believe that the carry-over effect of manure-N applied in spring has obscured any effect of mineral N treatment to be detected.

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REFERENCES

Buckman, H.O., 1910. Moisture and nitrate relationships in dry-land agriculture. *Proceedings of American Society of Agronomy* 2: 121-138.

Cambardella, C.A., T.B. Moorman, D.B. Jaynes, J.L. Hatfield, T.B. Parkin, W.W. Simpkins and D.L. Karlen. 1999. Water quality in Walnut creek watershed: Nitrate -nitrogen in soils, subsurface drainage water, and shallow groundwater. *Journal of Environmental Quality* 28: 25-34.

Comly, H.H. 1945. Cyanosis in infants caused by nitrates in well water. *Journal of the American Medical Association* 29: 112.

Cooper, R.L., N.R. Fausey and J.W. Johnson. 1999. Yield response of corn to a subirrigation/drainage management system in northern Ohio. *Journal of Production Agriculture* 12: 74-77.

Doty, C.W. 1980. Crop water supplied by controlled and reversible drainage. *Transactions of the ASAE* 23: 1122-1126.

Drury, C.F., C.S. Tan, J.D. Gaynor, T.O. Oloyo and T.W. Welacky. 1996. Influence of controlled drainage-subirrigation on surface and tile drainage nitrate loss. *Journal of Environmental Quality* 25: 317-324.

Drury, C.F., C.S. Tan, J.D. Gaynor, T.O. Oloyo, I.J. Van Vesenbeeck and D.J. McKenny. 1997. Optimizing corn production and reducing nitrate losses with water table control-subirrigation. *Soil Science Society of America Journal* 61: 889-895.

Eghball, B. 2000. Nitrogen mineralization from field-applied beef cattle feedlot manure or compost. *Soil Science Society of America Journal* 64: 2024-2030.

Elmi, A.A., C.A. Madramootoo and C. Hamel. 2000. Influence of water table and nitrogen management on residual soil NO_3^- and denitirification rate under corn production in sandy loam soil in Quebec. *Agriculture Ecosystem and Environment* 79: 187-197.

Elmi, A.A., C.A. Madramootoo, M. Egeh, G. Dodds and C. Hamel. 2002a. Water table management as a natural bioremediation technique of nitrate pollution. *Water Quality Research Journal of Canada* 37: 563-576.

Elmi, A.A., C.A. Madramootoo, M. Egeh, A. Liu and C. Hamel. 2002b. Environmental and agronomic implications of water table and nitrogen fertilization management. *Journal of Environmental Quality* 31: 1858-1867.

Elmi, A.A., T. Astatkie, C.A. Madramootoo, R. Gordon and D. Burton. 2005. Assessment of denitrification gaseous end-products in the soil profile under two water table management practices using repeated measures analysis. *Journalof Environmental Quality* 34:446-454.

FAO. 2000 Agriculture: Towards 2015/2030. Rome, Italy: Food and Agriculture Organization

Fogiel, A.C. and H.W. Belcher. 1991. Water quality impacts of water table management systems. ASAE Paper No. 91-2596. St. Joseph, MI: ASAE.

Gilliam, J.W. and R.W. Skaggs. 1986. Controlled agricultural drainage to maintain water quality. *Journal of the Irrigation and Drainage Engineering, ASCE* 112: 254-263.

Hatfield, J.L., D.B. Jaynes, M.R. Burkart, C.A. Cambardella, T.B. Morman, J.H. Brueger and M.A. Smith. 1999. Water quality in Walnut Creek watershed: Setting and farming practices. *Journal of Environmental Quality* 28: 11-24.

Jacinthe, P.A., W.A. Dick and L.C. Brown. 1999. Bioremediation of nitrate-contaminated shallow soils using water table management techniques: Nitrate removal efficiency. *Transactions of the ASAE* 42: 1251-1259.

Kalita, P.K. and R.S. Kanwar. 1993. Effect of water table management practices on the transport of nitrate-N to shallow groundwater. *Transactions of the ASAE* 36: 413-421.

Keeney, D.R. and T.H. DeLuca. 1993. Des Moines river nitrate in relation to watershed agricultural practices: 1945 versus 1980s. *Journal of Environmental Quality* 22: 267-272.

Keeney, D.R. and D.W. Nelson. 1982. Nitrogen: Inorganic forms. In *Methods of Soil Analysis: Part 2. Chemical and Microbiological Properties*, 2nd edition, eds. A.L. Page et al., 643-709. Madison. WI: American Society of Agronomy and Soil Science Society of America.

Kliewer, B.A. and J.W. Gilliam. 1995. Water management effects on denitrification and nitrous oxide evolution. *Soil Science Society American Journal* 59: 1694-1701.

Lord, E.I., P.A. Johnson and J.R. Archer. 1999. Nitrate sensitive areas: A study of large scale control of nitrate loss in England. *Soil Use and Management* 15: 201-207.

Patni, N.K., L. Masse and P.Y. Jui. 1998. Groundwater quality under conventional and no-tillage: I. Nitrate, electrical conductivity, and pH. *Journal of Environmental Quality* 27: 869-877.

Randall, G.W. and D.J. Mulla. 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. *Journal of Environmental Quality* 30: 337-344.

Sainju, U.M., B.P. Singh and W.F. Whitehead. 1998. Crop root distribution and its effects on soil nitrogen cycling. *Agronomy Journal* 90: 511-518.

SAS. 1999. SAS Online Doc®, Version 8. Cary, NC: SAS Institute Inc.

Skaggs, R.W., W.R. Reynolds and G.M. Chescheir.1999. Effects of subsurface drain depth on nitrogen losses from drained lands. ASAE. Paper No. 99-2086. St. Joseph, MI: ASAE.

Tait, R., C.A. Madramootoo and P. Enright. 1995. An instrumented, field scale research facility for drainage and water quality studies. *Computers and Electronics in Agriculture* 12: 131-145.

Tan, C.S., C.F. Drury, J.D. Gaynor, I. van Wesenbeeck and M. Soultani. 1996. Effect of water table management and nitrogen supply on yield, plant growth, and water use of corn in undisturbed soil columns. *Canadian Journal of Plant Science* 76: 229-235.

Wright, J.A., A. Shirmohammai, W.L. Magette, J.L. Fous, R.L. Bentson and J.E. Parsons. 1992. Water table management practice effects on water quality. *Transactions of the ASAE* 35: 823-831.

Zhou, X., A.F. MacKenzie, C.A. Madramootoo, W.J. Kaluli and D.L. Smith. 1997. Management practices to conserve soil nitrate in maize production systems. *Journal of Environmental Quality* 26: 1369-1374.