MANAGING WATER TABLES TO IMPROVE DRAINAGE WATER QUALITY IN QUEBEC, CANADA

C. A. Madramootoo, T. G. Helwig, G. T. Dodds

ABSTRACT. *The use of water table management as a potential environmental control measure to decrease total subsurface drainage outflow, and thus reduce N losses through leaching, was investigated at a monocropped maize (*Zea mays *L.) field site in southwestern Québec, for the 1998 and 1999 growing seasons (May to December). Water table depth (main plot) and N–fertilization rate (subplot) were arranged in a thrice–replicated split–plot design. Free drainage at a design water table depth of 1.0 m and subirrigation at a design water table depth of 0.6 m below the soil surface were used in factorial combination with two nitrogen fertilizer rates, 200 kg N ha^{-1} and 120 kg N ha^{-1}. Volumetric soil moisture at depths of 0.25 and 0.5 m, actual water table depth, and subsurface drain outflow were measured. Subsurface drainage water samples were collected on a flow–weighted basis and subsequently analyzed for nitrate levels. Drainage water discharge from the subirrigation plots was 20% lower than for the free drainage plots during the 1998 growing season, but no such decrease occurred in 1999 due to unusually dry conditions throughout the summer months. Overall, the mean nitrate–nitrogen concentrations in drainage water from the subirrigation plots were 74.0% and 80.3% lower than from the free drainage plots in 1998 and 1999, respectively. Total seasonal nitrate–N leaching losses in 1998 and 1999 were reduced by 80.4% and 58.34%, respectively, compared to free drainage. A close to 25% loss in yield under subirrigation in the wet year of 1998 emphasizes the need for a greater level of management of the water table under subirrigation than simply a fixed design water table depth.*

Keywords. *Drainage, Environment, Leaching, Nitrate, Soil moisture, Subirrigation, Water Table.*

Inadequate soil internal drainage is a problem in humid regions, especially for areas with fine–textured soils. Wet soil conditions decrease root respiration in plants, which in turn impedes growth and reduces yields. Artificial drainage enhances the productivity of poorly and imperfectly drained lands by lowering the water table depth and increasing root aeration. Across North America this practice has been used effectively to improve crop growth. Over 2.5 million hectares of cropland in the Canadian provinces of Ontario and Quebec are subsurface drained, mostly for maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) production (ICID, 2001).

Intensive agriculture relies increasingly on the use of agri–chemical inputs to increase productivity. However, subsurface drainage has been found to play a major role in the transport of plant nutrients from drained agricultural lands. Nitrates (NO_3^-), for example, are water soluble, and are easily leached to the subsurface drainage systems and then discharged into adjacent surface waters. This could worsen water quality problems by creating eutrophication and by increasing the concentration of nitrate nitrogen (NO_3^-–N) in surface and well waters above acceptable drinking water standards. In eastern Canada, NO_3^-–N concentrations as high as 40 mg L^{-1} have been measured in subsurface drainage waters (Milburn et al., 1990; Madramootoo et al., 1992), far exceeding the US EPA safe drinking water limit of 10 mg NO_3^-–N L^{-1} (45 mg NO_3^- L^{-1}).

Water table management has been identified as a best management practice that reduces nitrate losses from subsurface–drained soils while maintaining or enhancing yields (Brown et al., 1996; Evans et al., 1996; LICO, 1999). The practice of water table management consists of two main alternatives: controlled drainage and subirrigation. Both these practices reduce the impact of nitrate leaching by decreasing the volume of drainage water (Drury et al., 1996; Madramootoo et al., 1999) and by creating anaerobic conditions that promote denitrification (Gilliam and Skaggs, 1986; Wright et al., 1992; Elmi et al., 2000). Under controlled drainage, water is prevented from leaving the soil profile by means of a plugged or raised drainage outlet. The water table depth drops only due to evaporation, deep seepage, or when it is above the level of the altered drain outlet. On the other hand, subirrigation is achieved by installing a control structure at the drain outlet and supplying water to the drainage system in order to maintain an elevated water table depth in the field.

The primary aim of this study was to examine the effects of subirrigation on the quantity and quality of tile drainage water from maize fields in southwestern Quebec. This study also sought to characterize soil moisture under subirrigation

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and free drainage at different levels of the soil profile and at a frequency not previously undertaken in this region. The hypothesis that subirrigation could effectively decrease the magnitude of nitrate leaching was tested. The interactions between rainfall, water table depth, soil moisture, tile drainage outflow, and NO_3^-–N in the drainage water were also examined and quantified.

MATERIALS AND METHODS

EXPERIMENTAL SITE

Location and Layout

Experiments were conducted at an instrumented, 4.2 ha field site located near Côteau–du–Lac, Soulanges County, Quebec (74° 11′ 15″ lat., 45° 21′ 0″ long.), some 30 km west of the Macdonald Campus of McGill University. Site design and instrumentation is described fully in Tait et al. (1995). The upper soil layer (0–0.25 m) was a Soulanges very fine sandy loam (fine, silty, mixed, non–acid, frigid Humaquept) with an organic matter content of 5.0%, underlain by layers of sandy clay loam (0.25 to 0.55 m in depth) with an organic matter content of 1.5%, and clay (0.55 to 1.0 m depth) with negligible organic matter content. The bedrock was 21–22 m deep. Figure 1 shows a particle size analysis curve for four soil layers at the site (Broughton, 1972). The mean bulk densities were 1.63, 1.60 and 1.49 Mg m^{-3} in the 0–0.25 m, 0.25 to 0.55 m, and 0.55–1.0 m layers, respectively, while the mean hydraulic conductivities were 0.451, 0.364 and 0.138 m d^{-1}, respectively (Mousavizadeh, 1992). Figure 2 shows moisture retention curves for the soil according to depth (Broughton, 1972), allowing an estimation of saturated, field capacity, and wilting point soil water contents for different soil depths. Figure 2 shows both the theoretical field capacity at 1.0 kPa of suction and that measured in the field 48 h after a 27.5 mm rainfall. The actual field drainable porosity can be estimated at any depth by subtracting the field capacity from the soil moisture content at saturation. Mean soil physical parameters were obtained from six samples evenly distributed among the three blocks and showed a coefficient of variation (CV) inferior to 18%. The surface slope of the field was about 0.5%. Lateral subsurface drains were installed 15 m apart on a 0.3% slope at a maximum depth of 1.0 m (fig. 3).

Treatment Factors

Water table depth was the whole plot factor and fertilizer level the subplot factor in a thrice–replicated split–plot design. Each of the three 0.9 ha blocks was monocropped to maize and was divided into 8 treatment plots, each 15 m wide by 75 m long (1.125 ha; fig. 3). In each block, two drainage treatments were applied; conventional free drainage with drains 1.0 m deep and subirrigation at a design water table depth of 0.6 m. The plots received no surface irrigation. Nitrogen fertilizer was applied in a split dose: 23 kg N ha^{-1} banded as ammonium phosphate (18–46–0) at planting, and 97 kg N ha^{-1} or 177 kg N ha^{-1} broadcast as ammonium nitrate (34–0–0) one month after planting, resulting in rates of 120 kg N ha^{-1} (N_{120}) and 200 kg N ha^{-1} (N_{200}), respectively. Dates of seeding and fertilizer and pesticide application are presented in table 1.

Water Table Control

Eight drains from the easternmost block and the four drains from the easternmost plots in the middle block were individually routed to the East Building, and the remaining drains to the West Building (fig. 3). Twelve tipping buckets for monitoring subsurface drain outflow were housed in each building, one for each drainpipe. Elevated water tanks were installed on all drains (fig. 4). A ball valve located at the outlet of each drain allowed each individual drain to be used in either free drainage or subirrigation mode (fig. 4). For the subirrigated plots, the ball valve was closed and subirrigation water with no detectable NO_3^-–N (< 10μg L^{-1}) was pumped in from a 25–m deep high–production well (fig. 3). As the subirrigation water came from an extensive aquifer in the fractured bedrock, and no other nearby wells tapping this source have shown any detectable concentrations of NO_3^-–N, the water was sampled and tested for NO_3^-–N only

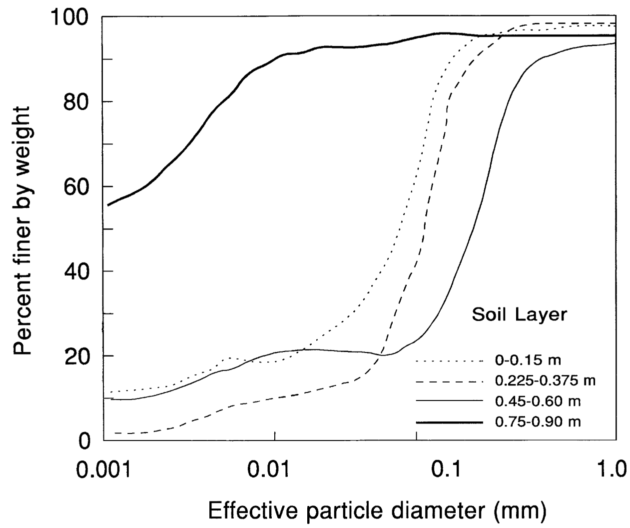

Figure 1. Soil particle analysis curves for different soil profile depths existing at the site.

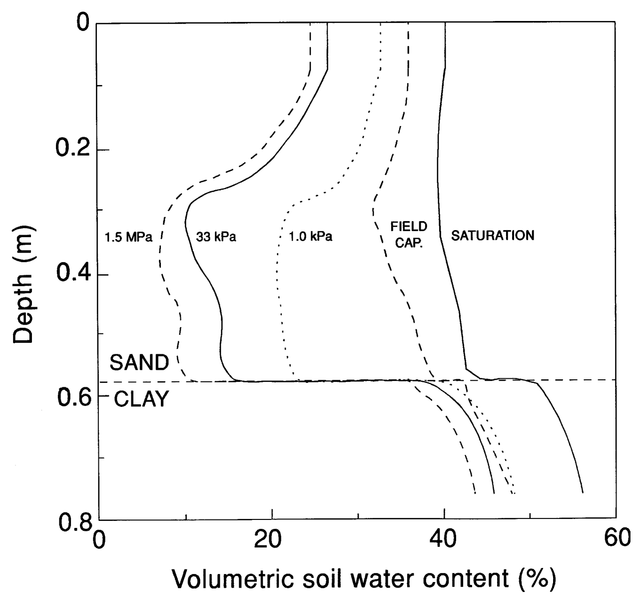

Figure 2. Moisture retention curves for different soil profile depths existing at the site (Broughton, 1972).

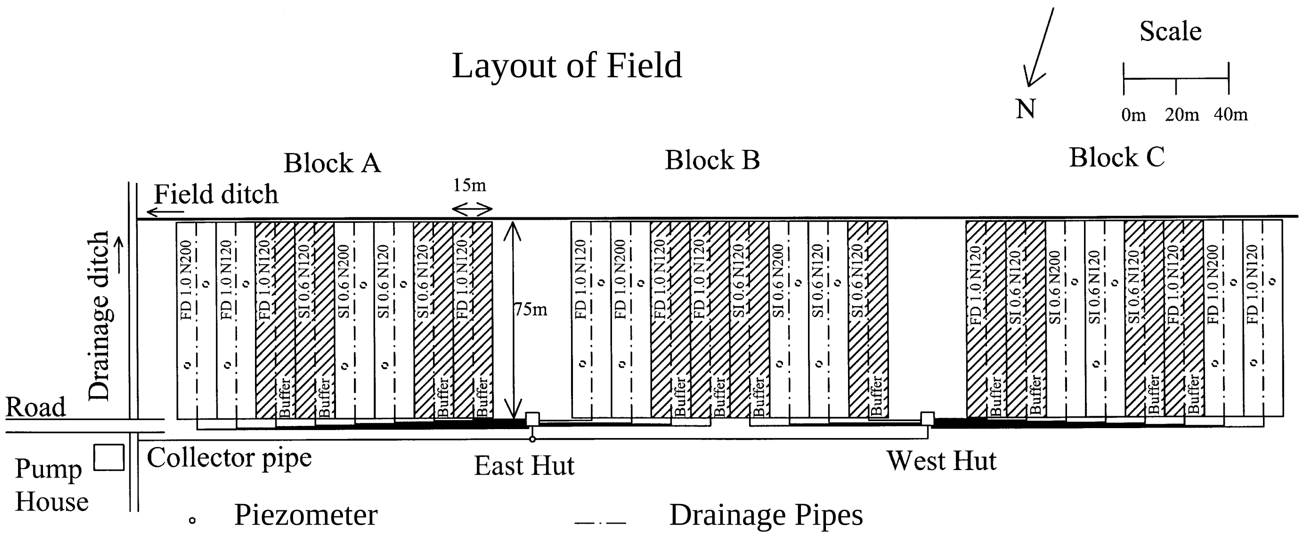

Figure 3. Experimental site layout: SI 0.6 = subirrigation, FD 1.0 = free drainage.

Table 1. Date of agronomic practices performed.

Agronomic practice	Date 1998	Date 1999
Seeding	May 8	May 4
N–fertilizer, 1st application (23 kg ha^{-1})	May 8	May 4
Subirrigation system turned on	May 30	May 30
N–fertilizer, 2nd application (97 or 177 kg ha^{-1})	June 8	June 10
Herbicide application: Marksman (4 L ha^{-1}) and Dual (2.5 L ha^{-1})	May 13	May 28
All drains opened for harvesting	Sept. 28	Sept. 17
Harvest	Oct. 20	Oct. 22

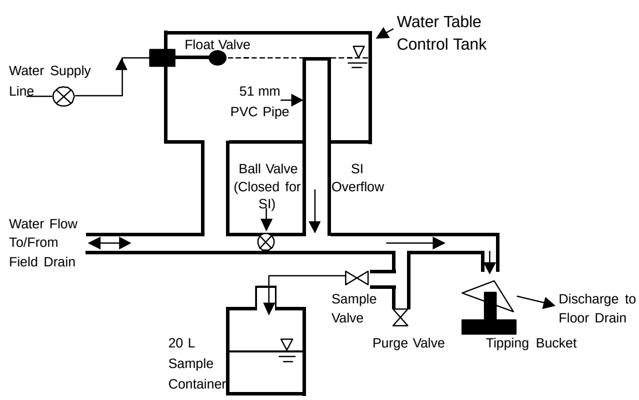

Figure 4. The subirrigation system.

once, at the beginning of the study. This water was pumped into a water control tank raised above the level of the drainpipes, until the height of water in the tank resulted in a design water table depth of 0.6 m in the field. When the water level in the tank was such that the design water table depth would be attained, a float valve closed off the incoming flow. When the water table depth was at its design level, drain flow could occur under subirrigation. After significant rainfall events, as the infiltrating rainwater raised the water table above the effective drain depth, drainage would occur until the water table depth had returned to its design depth. In both years, the subirrigation treatment remained static throughout the season, i.e., the design water table depth was not varied in response to greater or lesser rainfall.

A plastic barrier of double thickness, 6–mil (0.6 mm) polyethylene sheeting was installed to a depth of 1.5 m between plots (Tait et al., 1995). However, this did not sufficiently limit lateral flow from subirrigation treatment plots to adjacent free drainage plots, resulting in below–design water table depth on subirrigation plots, and higher drain flows on free drainage plots (Kaluli, 1996). Consequently, for this study, plots adjacent to subirrigation treatment plots were placed under subirrigation and those adjacent to free drainage plots under free drainage, resulting in 4 of the 8 plot–drains per block being dedicated to the 4 treatment combinations, and the remaining 4 plot–drains per block serving as buffers (fig. 3). All buffer plots received 120 kg N ha^{-1}.

Measurements

Soil Moisture Content

Soil moisture content was measured gravimetrically in June, July, and August. Soil samples were collected thrice weekly in 1998 and once a week in 1999. Two sampling depths (0–0.25 m and 0.25–0.5 m) and three sampling locations, located 20 m apart, diagonally across each plot, yielded six soil samples per plot per sampling date. Bulk densities of 1.63 Mg m^{-3} and 1.60 Mg m^{-3} were used for the upper and lower layers, respectively, to determine the volumetric SMC.

Water Table Depth

Water table depths were measured three times per week in each of the plots in both 1998 and 1999. Water table observation wells (perforated, 12–mm diameter polyethylene pipes with a geotextile sleeve) were installed to a depth of 1.4 m on the north and south sides of each plot (fig. 3). A water level sensor was used to monitor the depth of the water table, and water table depth averaged for each plot. A previous study at the site found no significant ($P > 0.05$) differences in water table depth within plots or across blocks (Qureshi et al., 1999).

Water Samples

Water sampling was done according to a flow–weighted composite strategy, i.e., the frequency of water sampling was set according to accumulated volume of drain flow. For both free drainage and subirrigation drains, 0.5 L samples were collected for every 1000 L of drain flow in the wetter year, 1998, and for every 500 L of drain flow in the drier year, 1999. In general, water samples were obtained and analyzed every two weeks during low flow periods, and up to twice a week during high flow periods. Composite samples accumulated in 20 L bottles, from which three replicate 20 ml sub–samples were removed manually and analyzed for NO_3^-–N, according to a colorimetric method modified from Keeney and Nelson (1982). The 20 L bottles were then emptied, rinsed with distilled water and returned to the sampler. Twenty water samples were taken in 1998, while drier weather in 1999 resulted in only 10 samples being taken.

The NO_3^-–N losses for the individual days between the last sampling and the current one were calculated by multiplying the mean NO_3^-–N concentration of the composite sample by its volume and dividing by the number of days. This assumes a fairly constant drain outflow, a condition which largely holds over the longer dry, low–flow periods, and which was less of an issue over short sampling periods during wet, high–flow conditions, particularly when losses are eventually expressed on a monthly basis.

Statistical Analysis

Soil moisture content, measured water table depth, drain flow converted to equivalent surface depth, NO_3^-–N concentration ([NO_3^-–N]) in drainage water, and total NO_3^-–N losses (concentration × flow) in the drain effluent were compared on a monthly mean or monthly total basis. Analysis of variance was done according to a split–plot design with water table depth as the whole plot factor and N–fertilization rate as the subplot factor, using the SAS procedure PROC GLM (SAS Institute, 1985). The significance criterion adopted was $P \leq 0.05$, or the 95% confidence level.

Results and Discussion

Precipitation

Table 2 shows the monthly precipitation reported by Environment Canada at the Côteau–du–Lac weather station, located approximately 500 m from the site. In 1998, the total monthly precipitation for the months of June and July were, respectively, 279% and 150% of the normal. These two months of high rainfall resulted in periods of shallow water tables, especially in the subirrigation plots. The response time for the drainage/subirrigation system to return to the desired water table depth after a major rain event was about one week.

Comparatively, 1999 was a dry summer. While total precipitation for June and July were close to the normal, May and August were 23% and 35% lower, respectively, than the normal. For much of the summer of 1999, the water table depth in the free drainage plots remained deeper than 1.0 m and were thus below the depth of the drain. Zero drain outflow resulted in zero NO_3^-–N outflow in these periods.

Table 2. Monthly precipitation, 1998, 1999, and 30–year (1961–1990) mean.

	Precipitation (mm)		
Month	1998	1999	Mean (1961–1990)
April	33.4	25.0	73.5
May	69.6	53.2	68.3
June	229.8	94.6	82.5
July	128.4	103.6	85.6
August	101.0	64.8	100.3
September	80.8	168.6	86.5
October	66.2	107.4	72.5
November	53.0	31.4	92.2
Seasonal total	762.2	648.6	661.4

Water Table Depths

Water table depths for both subirrigation and free drainage treatments in 1998 and 1999 are presented in figure 5. Measurements presented are limited to the period when the water table management system was functional. In both years, except for the months of June and July in 1998, water table depth on a monthly mean basis was significantly ($P \leq 0.05$) deeper under free drainage than under subirrigation (fig. 5). These differences in measured water table depth as a consequence of water table settings were also found at this site in the past (Qureshi et al., 1999) and similarly elsewhere (Drury et al., 1996).

During the summer of 1998 the poor performance of the drainage component of the subirrigation system during wet periods in June and July, when rainfall was double the norm, led to water table depths on average 0.11 m above the design water table depth (fig. 5), and on some occasions to ponding of water on the field. When ponding occurred, the subirrigation system had to be manually shut off for 12–24 hrs to allow drainage of excess water. The average water table depth for the remainder of the summer was 0.1 m below the design water table depth. From mid–July to mid–August 1998 the difference between measured water table depth for the subirrigated vs. free drainage plots gradually increased

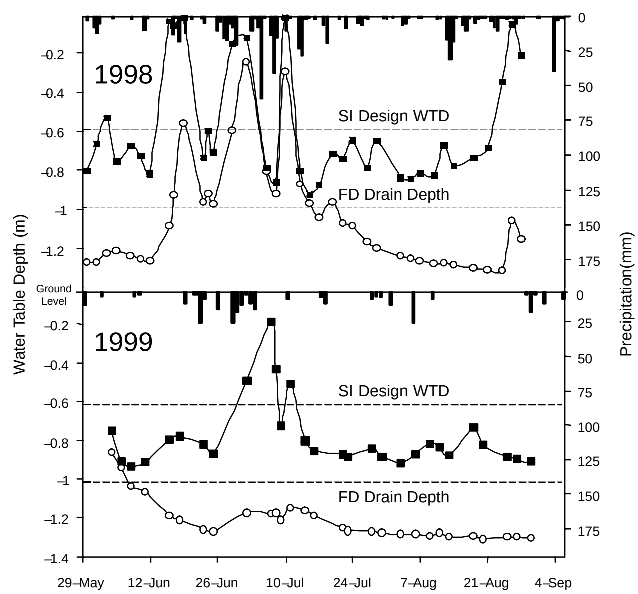

Figure 5. Measured water table depth (m) under subirrigation (■) and free drainage (FD, ❍), 1998 and 1999.

under relatively low rainfall conditions. For free drainage plots, except for the period in June and July 1998 when water tables were above the drains, water table depths remained, during dry periods, on average 0.2 m below the drains.

Under subirrigation the mean water table depth over the full summer 1999 period (May to August) was 0.1 m below the design water table depth, and 0.23 m below for a 50–day dry period (July 15 to Sept. 5). The water table in the free drainage plots remained below the drains (1.0 m) for most of the summer, and was at times at some sampling locations deeper than the water table observation wells (i.e., below 1.3 m). The seasonal mean WTdepth in the free drainage plots was 1.2 m in 1999.

Yields were 25% lower in the subirrigated vs. free drainage plots in 1998, whereas this difference was only 1.7% in the drier 1999 (table 3). At harvest in 1998, the maize stalks were about one meter shorter in the subirrigated than in the free drainage plots. It is evident that over the two–year period it was difficult to maintain water table depths at design levels in the subirrigated plots (fig. 5). While a static subirrigation design water table depth may be adequate for dry seasons or periods, a higher level of management of the water table is required during rainy periods/seasons.

Soil Moisture Content

Although the soil depths sampled (0–0.25 m and 0.25–0.50 m) for soil moisture content were shallow relative to the design water table depth, on a monthly mean basis the soil moisture content of subirrigation plots was significantly greater ($P \leq 0.05$) than that of free drainage plots for all month by year by sampling depth combinations except for the period extending from June and July 1998 when no significant difference ($P > 0.05$) existed at either sampling depth (figs. 6, 7). This lack of difference in soil moisture content between water table depth treatments is attributable to the two–fold greater than normal precipitation in June–July 1998 (table 2), and the resulting elevated water tables from mid–June to mid–July (fig. 5). During this period the water table was at times situated within the range of soil sampling depth (fig. 5), leading to differences in moisture being obscured by the soil being at or near saturation.

Soil moisture content graphs showed a similar trend for both water table depth treatments, and were separated by 0–10% moisture content through June and July, with a maximum difference of about 15% occurring in August of both years (fig. 6, 7). In 1998, soil moisture contents averaged over the entire growing season for the free drainage and subirrigation treatments were 37.4% and 45.0%, and 29.4 and 35.1%, for the 0–0.25 m (fig. 6) and 0.25–0.50 m (fig. 7)

Table 3. Maize grain yield, 1998 and 1999. Significance of treatment factors and yield comparisons.

Source	d.f.	Pr > F	
		1998	1999
MODEL	7	0.2224	0.5533
BLOCK	2	0.6105	0.2502
WTD	1	0.0019	0.7349
NITR	1	0.6846	0.5266
NITR[a] WTD	1	0.2666	0.6901
Water table depth (m)	Applied N (kg ha^{-1})	Yield (Mg ha^{-1})[a]	
0.6 (subirrigation)	all	6.56b	9.53a
1.0 (free drainage)		8.75a	9.69a
All	120	7.79a	9.45a
	200	7.52a	9.77a
0.6 (subirrigation)	120	7.09 $\pm$1.15	9.27 $\pm$0.44
	200	6.04 $\pm$0.66	9.78 $\pm$0.88
1.0 (free drainage)	120	8.49 $\pm$1.02	9.64 $\pm$0.56
	200	9.01 $\pm$0.23	9.75 $\pm$1.31

[a] For the WTD (water table depth) and NITR (rate of N fertilization) factors considered singly, columnwise values sharing the same letter are not significantly different ($P > 0.05$). For WTD and NITR considered in combination values represent mean $\pm$ standard deviation.

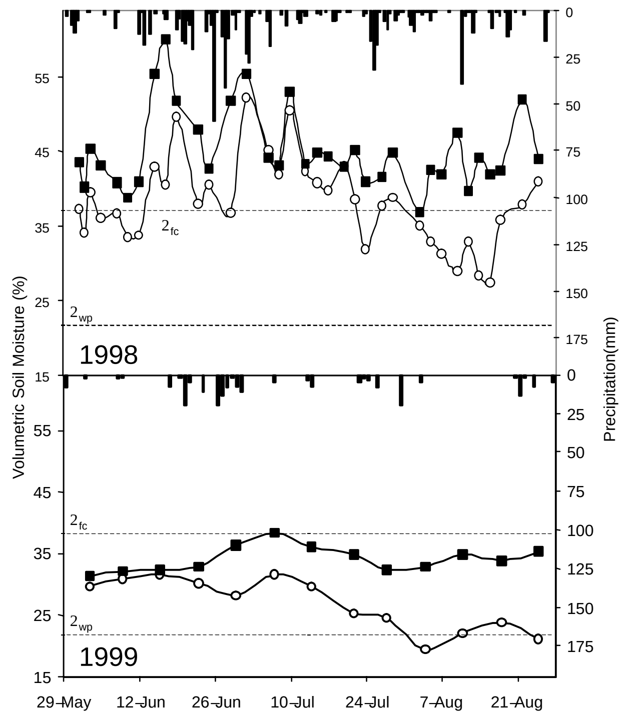

Figure 6. Volumetric soil moisture content (%) under subirrigation (■) and free drainage (❍) for the upper soil layer (0–0.25 m), 1998 and 1999.

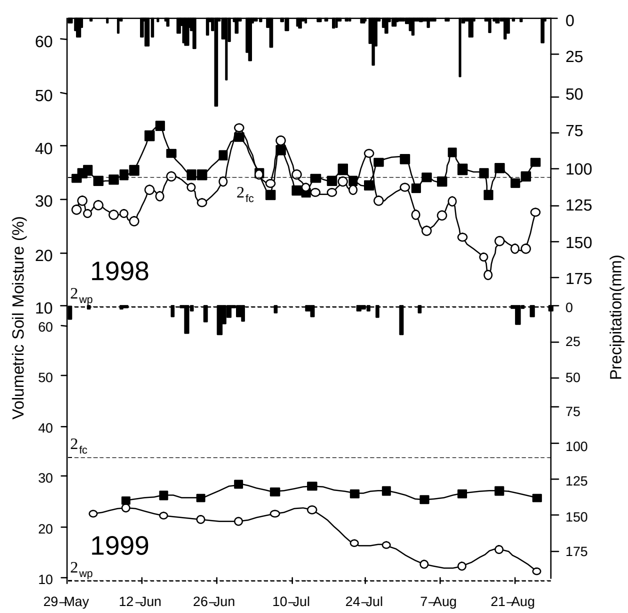

Figure 7. Volumetric soil moisture content (%) under subirrigation (■) and free drainage (❍) for the lower soil layer (0.25–0.50 m), 1998 and 1999.

soil layers, respectively. Under subirrigation, for the 0–0.25 m soil depth range, soil moisture remained over field capacity for all but one sampling date in the season (fig. 6). For free drainage plots, soil moisture exceeded field capacity during the wet June and July, but concurrent with the drop in water table depth that began in late July (fig. 5), soil moisture levels dropped below field capacity. Under subirrigation, for the 0.25–0.50 m soil depth range, soil moisture remained at or near field capacity (fig. 7) except for the wet June–July period, while for free drainage plots, outside the wet period soil moisture remained below field capacity, particularly after July when water tables depth differences between subirrigated and free drainage plots began to increase (fig. 5). At no time in 1998 did soil moisture drop below the wilting point moisture content in either soil depth range under either drainage treatment (fig. 6, 7).

In 1999, for the 0.25–0.50 m soil layer the mean values for soil moisture content for the free drainage and subirrigation treatments were 26.5% and 34.2%, and 18.4% and 26.3% for the 0–0.25 m (fig. 6) and 0.25–0.50 m (fig. 7) soil layers, respectively. As expected, soil moisture was 5%–8% higher over the season for the subirrigation treatment than for the free drainage treatment. Similar differences were reported for this site in 1994–1995 (Qureshi et al., 1999). Under subirrigation, for both soil depth ranges, soil moisture remained below field capacity for all but one sampling date in the season (fig. 6), as did that measured under free drainage. In both soil depth ranges soil water content approached the wilting point capacity in August (figs. 6, 7).

The poor yield under subirrigation compared to free drainage in 1998, but not 1999, can clearly be attributed to the significant portion of 1998 during which soil moisture exceeded field capacity in the subirrigated plots, whereas in 1999 soil moisture in these plots remained below the field capacity, but above the wilting point (figs. 6, 7).

Drain Outflow as Equivalent Surface Depth

As expected, nitrogen fertilization rate had no significant effect ($P > 0.8$) on drain outflow as equivalent surface depth (mm). Water table management was implemented from 30 May to mid–September (table 2). In both years, no significant differences ($P > 0.05$) in drain outflow were observed between free drainage and subirrigation plots for the months of August and November, the latter because the drain outflow was so minimal, the former because the subirrigation plots had been returned to free drainage since mid–September (fig. 8).

Drain outflow for free drainage and subirrigation treatments in June and July 1998 were no less than 25 mm, and at least 4.8–fold greater than in their corresponding treatments/months of 1999 (fig. 8). This reflected the 143% and 24% higher precipitation in 1998 than 1999. In June and July 1998, drain outflow was significantly ($P \leq 0.01$) lower (48% and 15%, respectively) in the subirrigation plots than in the free drainage plots. This higher drainage outflow under free drainage is likely attributable to the water table depth under free drainage remaining well above the drains (1.0 m depth) from mid–June to the end of July due to the prevailing wet weather (fig. 7). No significant difference ($P > 0.05$) in outflow rate occurred in August of either year.

Comparatively, in 1999 the water table depth in the free drainage plots remained below drain depth from June onwards (fig. 7), monthly drainage depth in June and July were no more than 13 mm. As one would expect, June drainage outflow was significantly ($P \leq 0.05$; 4–fold) greater for free drainage than subirrigation as both treatments showed water table depth up to 0.3 m below effective drain depth. However, in July drainage outflow was significantly ($P \leq 0.01$; >10–fold) greater for subirrigation than free drainage (fig. 8). Unlike, June where water table depth for both free drainage and subirrigation treatments were well below the effective drain depth, in July water table depth under subirrigation rose above drain depth, while that for the free drainage, while showing a slight rise, remained well below drain depth. Thus for June and July 1998 (a wet year) combined, subirrigation significantly ($P \leq 0.05$) reduced drainage outflow, but had no overall ($P > 0.05$) effect over the same period in a year of more average rainfall (1999).

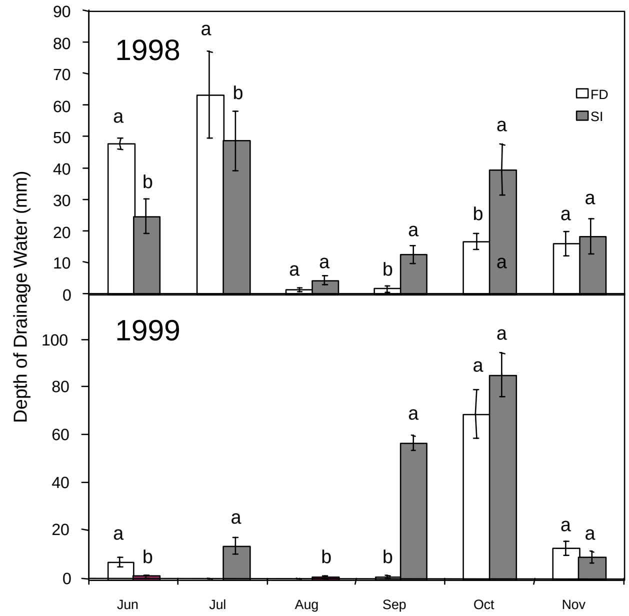

Figure 8. Mean monthly subsurface drain outflow as equivalent surface depth (mm) under subirrigation (SI) and free drainage (FD), 1998 and 1999.

Drainage outflows for September and October were, except for free drainage in September (<3 mm in both years), much greater in 1999 than 1998 (fig. 8). Increases in drainage outflow from 1998 to 1999, were 270, 212, and 64% for subirrigation–September, free drainage–October and subirrigation–October, respectively. These increases can be attributed to the 95% and 48% greater than normal precipitation in September and October 1999, compared to the close to normal (<±10%) precipitation for these months in 1998 (table 3).

In September 1998 and 1999, subirrigation drainage outflow was significantly ($P \leq 0.05$) greater (5.7 and 74–fold, respectively) than that for free drainage plots (fig. 8). The greater difference in outflow between September free drainage and subirrigation in 1999 than 1998 may be attributed to the fact that in 1998 the subirrigation and free drainage treatments remained in operation throughout September (end Sept 28), whereas in 1999, under more rainy conditions, subirrigation was ended some 11 days earlier, releasing a greater proportion of subirrigation–accumulated soil water.

In October 1998, after subirrigation plots had been returned to free drainage, the drainage outflow was significantly greater ($P \leq 0.05$; 2.4 fold) under former subirrigation plots than under free drainage, though this difference was no longer significant ($P > 0.05$) in November. The continuing free drainage to subirrigation difference in October 1998 represents the holdover effect of the additional water maintained in the subirrigation plots through September, which drained out in October. A similar trend ($P \leq 0.25$) was apparent for October 1999, where drainage outflow of former subirrigation plots was 25% greater than that for free drainage plots, but again no significant difference ($P > 0.05$) was apparent in November. The fact that the subirrigation treatment holdover effect was greater in 1998 than in 1999 may be in part attributable to the differences in rainfall between 1998 and 1999. While the 1998 growing season was wetter than normal overall, September and October rainfall were 6.6% and 8.7% below normal, respectively. In contrast, while 1999 was a slightly drier than normal growing season overall, September and October rainfall were 95% and 48% above average, respectively. In 1998 the late removal of the subirrigation treatment (Sept. 28) and low rainfall would have meant that a greater proportion of the October drainage outflow in former subirrigation plots would have been contributed from subirrigation–stored water, rather than rainfall. In 1999, when subirrigation was turned off 11 days earlier than 1998, the former subirrigation plots would have had close to two weeks under free drainage before October began. Combined with above average rainfall, the proportion of drainage outflow contributed by subirrigation–stored water compared to rainfall would have been much less in 1999, leading to the subirrigation treatment having a less important holdover effect.

In 1998, over the entire period of subirrigation, the subirrigation drains showed about 25% less drainage outflow than free drainage drains (109 mm vs. 150 mm, respectively; $P \leq 0.06$). This corresponds with the 20%–30% decrease noted from other studies (Drury et al., 1996; Evans et al. 1996). From September 30 to freeze–up in December, the drained flow was higher in the former subirrigation plots than the full–season free drainage plots, suggesting that a significant portion of the flow from former subirrigation–plots in this period was from moisture stored in the profile, rather than from precipitation. However, in 1999, over the entire period of subirrigation, the subirrigation plots showed a close to 4–fold greater drain flow than free drainage plots (32 mm vs. 8 mm, respectively; $P \leq 0.07$). While this difference is contrary to that expected, one must point out that the overall drainage flow during the subirrigation period was very low (<0.3 mm day^{-1} for subirrigation).

NO_3^-–N Concentrations in Drainage Water

While the effect was not statistically significant in 1998 ($0.08 < P < 0.17$) or in September 1999 ($0.05 < P < 0.052$), for the remaining months of 1999 NO_3^-–N concentrations in drainage water were significantly less ($P \leq 0.03$) under subirrigation than under free drainage (fig. 9). Overall it is clear that NO_3^-–N concentrations in drainage water were greatly reduced by the implementation of subirrigation, both during the subirrigation and in the subsequent months of October and November (fig. 9). Overall the seasonal mean NO_3^-–N concentrations in drainflow from the subirrigation plots were 74.0% and 80.3% lower than from free drainage plots in 1998 ($P \leq 0.09$) and 1999 ($P \leq 0.025$) respectively. The differences observed during the subirrigation period, and particularly afterwards, are likely attributable to enhanced denitrification under the wetter soil conditions (fig. 3, 4). Drury et al. (1996) reported a 25% decrease in drainage water NO_3^-–N concentration under water table management, compared to conventional drainage.

The rate of N fertilizer applied had no significant effect ($P < 0.05$) on NO_3^-–N concentration in the drainage outflow water. However, some trends in NO_3^-–N are apparent over the season. These trends are most apparent for the free drainage plots and will be discussed in terms of this treatment; however, these same trends also generally hold for the subirrigation plots. From June to August there was a gradual decline in NO_3^-–N concentration in the drain outflow, while from September to November a gradual increase occurred. While the mean June–August NO_3^-–N concentration under free drainage was roughly the same in both years (difference < 3%), in 1998 the rate of decline in NO_3^-–N concentration was much sharper than in 1999 (fig. 9). The quicker June to August decline, but higher initial June NO_3^-–N concentration, in 1998 is likely related to the differences in precipitation patterns between the two years. In 1998, three >10 mm rainfall events occurred in the week following the second (surface) N fertilizer application (June 8; fig. 4), and as mentioned previously, June and July precipitation were well above average. These conditions would have contributed to an initially high soil water NO_3^-–N concentration and rapid loss of NO_3^-—N through leaching (fig. 10) given the high drainage depth (fig. 7). Conversely, in 1999, only two rainfall events of >10 mm occurred in the two weeks after the second fertilizer application (June 10; fig. 3), the first some 10 days after application. Additionally, June and July rainfall while above average were much less than in 1998. Consequently a flush in NO_3^-–N concentration was less likely to occur, and

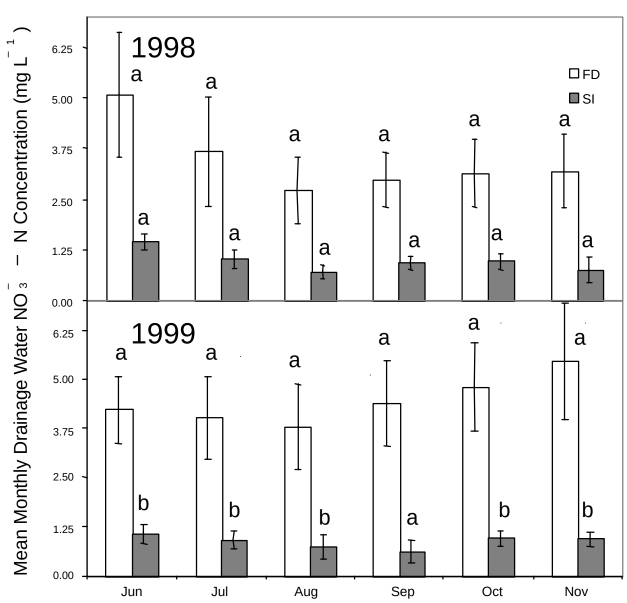

Figure 9. Mean monthly NO_3^-–N concentration (mg L^{-1}) in subsurface drainage water under subirrigation (SI) and free drainage (FD), 1998 and 1999.

leaching losses (fig. 10) would be much less under the no more than 10 mm of drain flow under free drainage (fig. 8).

The pattern in NO_3^-–N concentration from September–November was a mirror image of that for June–August (fig. 9). A gradual increase in NO_3^-–N concentration occurred over this period, which was greater in 1999 than 1998. Overall NO_3^-–N concentrations in September–November 1998 were lower than in 1999, likely due to the important NO_3^-–N leaching losses in June and July (fig. 10). The above average rainfall in September and October and the season high monthly free drainage depths in October and November, following upon the relatively dry, low flow conditions of the preceding month, would have contributed to residual soil NO_3^-–N suddenly reaching drainage waters.

NO_3^-–N Leaching Losses

Except in July, August, and November 1999, where totalled NO_3^-–N leaching losses were less than 0.1 kg ha^{-1}, significant differences ($P \leq 0.05$) between subirrigation and free drainage plots in terms of leached NO_3^-–N occurred only in the rainy months of June and July 1998 and October 1999 (fig. 10). The rainy month of September 1999 showed a non–significant ($P > 0.5$), but close to ten–fold difference in NO_3^-–N leaching losses. In 1998, the months of June and July accounted for 86% and 61% of seasonal (June–November) leached NO_3^-–N losses under free drainage and subirrigation, respectively. In 1999, the months of September and October accounted for 90% and 93% of seasonal leached NO_3^-–N losses under free drainage and subirrigation, respectively.

In 1998 the mean total NO_3–N loss from the free drainage plots was 7.2 kg ha^{-1}, whereas the mean total loss from the subirrigation plots was 1.41 kg ha^{-1}. In 1999, total NO_3–N losses from the free drainage plots were about 3.0 kg ha^{-1} and about 1.2 kg ha^{-1} from the subirrigation plots. The significant ($P \leq 0.03$) overall reductions in leaching were 80.4% and 58.34%, respectively, in the subirrigation plots compared to free drainage plots in 1998 and 1999. The reduction in NO_3^-–N leaching under subirrigation compared to free drainage was about 85% each in June and July 1998, and 69% in October 1999. Other researchers have reported similar results. For example, under water table management, seasonal decreases of 44% and 45% were recorded by Drury et al. (1996) and Evans et al. (1996), respectively, compared to conventional drainage. At the same site as ours, but under different fertilizer and cropping practices, Kaluli et al. (1999) found a 70% decrease in NO_3^-–N leaching under subirrigation.

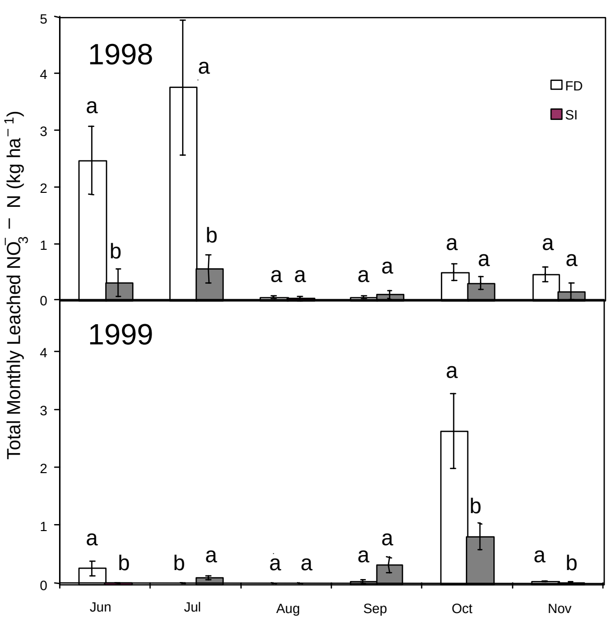

Figure 10. Mean monthly NO_3^-–N leached (kg ha^{-1}) in subsurface drainage water under subirrigation (SI) and free drainage (FD), 1998 and 1999.

Summary and Conclusions

The effects of water table management on nitrate leaching from subsurface drains were examined at an experimental site at Côteau–du–Lac, Quebec. The interactions between rainfall, water table depth, soil moisture, volume of drained water outflow, concentration of nitrates in the drainage water, and total nitrate–N lost were examined and quantified. The fertilizer treatment showed no statistically significant ($P > 0.05$) effect on any of the latter three parameters.

It was difficult to maintain water table depth at the desired levels in the subirrigation plots for both years. During wet periods, the water table depth would often rise above 0.6 m, even resulting in surface ponding in June of 1998. During dry periods, the water table depth fell to as low as 0.85 m. Under free drainage, with drains open at a 1.0 m depth, the water table depth rose to within 0.25 m (July 1998) of the surface and for much of 1999 was below 1.2 m.

Compared to the free drainage treatment, soil moisture was significantly increased ($P \leq 0.05$) by the subirrigation treatments, over the sampling period and at both sampling depths. In 1998 the average difference in volumetric soil moisture between the subirrigation and free drainage plots was 7.6% in the upper layer (0–0.25 m) and 7.7% in the lower layer (0.25–0.50 m). In 1999 the average difference between the WT treatments was 5.7% in the upper layer and 7.9% in the lower layer. The maximum difference for both years occurred in August, at a value of approximately 15% for both soil depths.

The drainage discharge was reduced by 20% during the summer of 1998 due to water table management. During the autumn months following the water table management period, greater amounts of water were released from the subirrigation drains for both years. In 1999 there was no apparent decrease in drainage discharge from the subirrigation plots due to dry conditions and the depths of the water tables. For most of summer 1999, the water table in the free drainage plots was below the depth of the drain. Hence the basis of comparison was not as good as in 1998. Under such dry conditions, water table management can function as a NO_3^-–N leaching control measure by enhancing denitrification, but not by reducing the drainage outflow from conventional free outlet drainage pipes. NO_3^-–N levels in drainage water were reduced, on average, by 74.0% in 1998 and 80.3% in 1999 in the subirrigation plots. Total NO_3^-–N losses in the subirrigation plots were reduced by 80.4% and 58.34% from June to November 1998 and 1999. Thus, drainage water quality was clearly improved by subirrigation.

In 1998 maize grain yields were 8.75 Mg ha^{-1} and 6.56 Mg ha^{-1} for the free drainage and subirrigation treatments, respectively, showing a significant ($P \leq 0.005$) decrease under subirrigation. During much of 1998 soil moisture was at or above field capacity due to the high rainfall, and the water table reached the surface on some occasions. The water table often rose above the desired depth of 0.6 m below the soil surface, and this resulted in the plants suffering from wet stress or waterlogging. Rather than a static subirrigation, a management scenario where subirrigation would be switched on and off depending on soil moisture conditions would have obviously benefited the crop. However, such a level of management, achieved by turning on and off the well–water pump and/or opening the drains to free drainage would be much more time–intensive, and would require taking frequent water table depth readings, something not all farmers in the region would be able to do. Grain yields in 1999 were similar for subirrigation and free drainage treatments (9.53 Mg ha^{-1} and 9.69 Mg ha^{-1}), and higher than in 1998. In 1999, it may have been possible to obtain higher crop yields under subirrigation, as reported elsewhere (Brown et al., 1996; Evans et al., 1996), with a more aggressive use of subirrigation (i.e. higher design water table depth). In either case subirrigation is a practice, which while it clearly reduces NO_3^-–N leaching losses, necessitates close management to fulfill its full agronomic potential.

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