Groundwater Monitoring&Remediation

Effects of Fall vs. Spring Plowing Forages on Nitrate Leaching Losses to Groundwater

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Abstract

High levels of nitrate leaching losses from potato rotation systems have caused concerns for both drinking water quality and aquatic ecosystem protection in Prince Edward Island (PEI). Paired-field experiments were carried out in commercial fields to evaluate the potential of delayed plowing forages within potato rotation from fall to spring on reducing nitrate leaching at two separate sites in PEI during 2010 and 2013. Monitoring showed that fall plowing resulted in elevated tile-drain nitrate concentrations compared to spring plowing, probably mainly due to crop residue mineralization during fall which was hastened by earlier herbicidal termination of forage (i.e., herbicidal killing) at Site 1. A similar trend was also observed regarding nitrate concentrations of shallow groundwater at Site 2 during the forage phase. The practice of delaying the plowing of forages and/or associated earlier herbicidal termination of forage until spring reduces forage-phase nitrate leaching loss by 20 to 61%, and should therefore be encouraged for nitrate mitigation. The study also demonstrated that only a small fraction (9.6 to 22%) of the fall plow-down forages decayed during the forage phase and a large portion was retained in the soil into the next season. Growers should consider accounting for some of the carried-over N for the subsequent crops regardless implementing fall or spring plowing.

Introduction

Prince Edward Island (PEI) is the smallest province in Canada, yet it contributes about one-fourth of the Canadian potato production (Statistics Canada 2012), and the potato industry plays a critical role in the local economy. Intensive potato production is conducted on sandy soils underlain by a semi-confined or unconfined sandstone aquifer, which provides all the drinking water in PEI (Commission on Nitrates in Groundwater in PEI 2008). High levels of nitrate leaching losses from the production systems have been linked to the contamination of groundwater (Savard et al. 2007). The contamination is evidenced by the fact that well water in most of the potato production areas exhibits nitrate levels elevated significantly above natural background level (i.e., 1 mg N/L), and in some cases, elevated above the safe level for drinking. Statistics based on a database of 9512 well samples for the period 2004 and 2008 indicates nitrate concentration of well water averaged at 3.7 mg N/L across the island and at 5 and 10 mg N/L in 14% of the island's watersheds; nitrate concentration in 4% of wells (15 and 20% in the intensive farming watersheds) exceeds the safe level for drinking (PEI Department of Environment, Labor and Justice internal data). Groundwater contributes to as much as 66% of annual flow in a typical stream in PEI, and nitrate-enriched groundwater discharges can lead to surface water contamination and aquatic ecosystem deterioration (Jiang and Somers 2009). Elevated nitrate in surface water has been suggested as one of the factors associated with the anoxic events prevailing in many estuaries in PEI (Bugden et al. 2014). Thus, nitrate contamination of groundwater is of concern for both drinking water quality and aquatic habitat protection in PEI (Commission on Nitrates in Groundwater in PEI 2008). Growers in the region are facing unprecedented pressure to mitigate nitrate contamination while maintaining their market competiveness.

This important water quality issue is preferably mitigated through implementing Beneficial Management Practices (BMPs) (Commission on Nitrates in Groundwater in PEI 2008), and it is imperative to develop effective BMPs for reducing nitrate leaching while sustaining optimal potato production in PEI. Potatoes are commonly grown in rotation with grain underseeded with forages, with the latter being plowed down in the fall of the third season as green manure. Previous work has shown that a high proportion of nitrate leached from these systems occurs during the nongrowing season after potato harvest (Sanderson and McLeod 1994; Jiang et al. 2012). This was because the potato crop usually receives high fertilizer N inputs in order to meet industry tuber yield and size requirements, whereas its N use efficiency is very low owing to its shallow root system. The apparent recovery of applied fertilizer N in the potato crop was reported to commonly range from as low as 40 to 60% (Zebarth and Rosen 2007; Vos 2009). Some BMPs, including planting cover crops and incorporating high C/N (carbon/nitrogen) ratio wheat straw mulch for nitrate immobilization upon potato harvest, were tested for reducing

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nitrate leaching losses during the potato phase (Milburn et al. 1997). These BMPs did not work effectively because the commonly grown long-season potato variety does not leave sufficient time for the cover crops to establish before the soil is frozen, and incorporating straw mulch disturbs the soil immediately before the winter season leading to a high potential risk of erosion.

While searching for effective BMPs for mitigating nitrate leaching during the potato phase remains a research priority in PEI, some experiments have been performed to explore the opportunities of reducing nitrate leaching during the forage phase as high levels of nitrate leaching were also observed upon fall forage plow down in PEI (Sanderson and McLeod 1994). The rotation forages usually include N-rich leguminous crops with low C/N ratio (e.g., red clover) intended for maintaining soil organic matter (SOM) for optimal production. When being plowed down in the fall, a portion of these forages release nitrate via mineralization, which leaches from the soil profile with the excessive moisture during the wet offseason in PEI. Soil-based plot-scale tests suggest that delayed plowing reduces mineralization of the forages and, subsequently, more N is retained in the soil profile for the following crops (Sanderson et al. 1999; Sanderson and Macleod 2002). Growers can potentially reduce fertilizer N input for the succeeding crops by crediting this carried-over N, which would save costs on fertilizer and reduce nitrate leaching due to less fertilizer N input during the following season. In the absence of alternative BMPs for nitrate mitigation, delayed forage plowing appears promising for mitigation of nitrate leaching in PEI; however, the magnitudes of the environmental and economic benefits of the BMP are largely unknown. This BMP was selected for further testing in commercial fields at two separate sites in the Souris River watershed in PEI during the period of October 2010 to March 2013. The objective was to evaluate the forage-phase nitrate leaching reduction due to postponing plowing forages from fall to spring.

Materials and Methods

Experimental Setup

The experiments were performed at two separate sites within the Souris River watershed (53 km^2), in the eastern part of PEI. Site 1 (46°23′57″N/62°20′45″W) is located in the western portion of the watershed, and two adjacent fields were paired for fall (S1FP = 34 ha) vs. spring (S1SP = 8 ha) plowing treatments (Figure 1). The cropping sequence in the two fields was barley (2009), -mix of red clover and timothy as forages (2010), -soybean (2011), -potato (2012), -barley (2013). The forages on S1FP and S1SP were plowed down in the fall of 2010 and the spring of 2011 respectively with pre-plow herbicide (i.e., glyphosate) treatments. Site 2 (46°22′11″N/62°15′24″W) is situated in the southeast portion of the watershed, with one field (7 ha) being split into half for fall plowing (S2FP) and spring plowing (S2SP) treatments respectively (Figure 2). The cropping sequence was barley (2009), -mix of red clover and ryegrass as forages (2010), -potato (2011), -barley (2012), -and a mix of red clover and ryegrass as forages (2013). The forages on S2FP and S2SP were plowed down in the fall of 2010 and the spring of 2011 respectively without herbicidal treatment. The two sites are characterized with sandy loam soils within the top 45 cm of the soil profile with SOM of 3.2 to 3.8% and pH of 6.0 to 6.2. More details of the experimental management practices are summarized in Table 1.

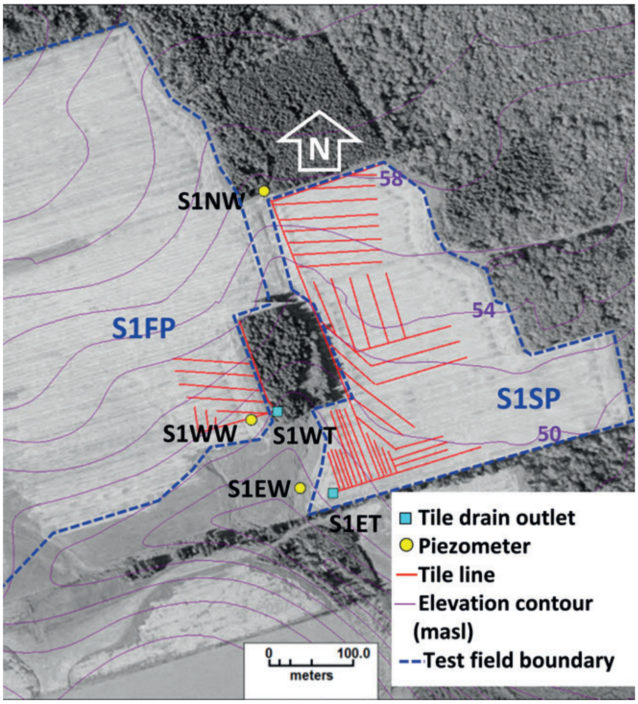

Figure 1. Experimental fields and monitoring stations indicated on the 2000 orthorphoto at Site 1 (all tile lines in S1FP discharge into a header line with outlet at S1WT and all tile lines in S1SP discharge into a header line with outlet at S1ET).

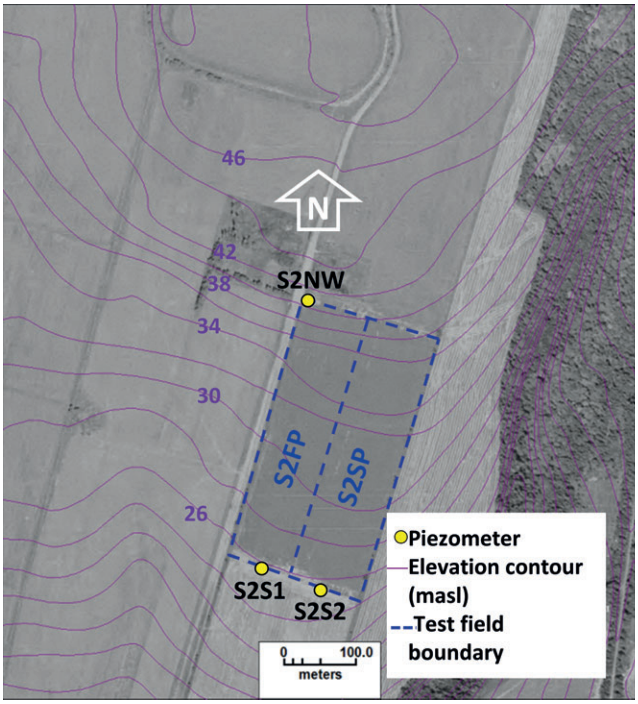

Figure 2. Experimental field and piezometers indicated on the 2000 orthophoto at Site 2.

Table 1

Experimental Treatments and Management Practices

Season/Year	Site 1	Site 2
Spring 2009	Barley under-seeded with mix of red clover/timothy and applied $N = 60$ kg N/ha as NH_4NO_3 at planting	Barley under-seeded with mix of red clover/ryegrass and applied $N = 60$ kg N/ha as NH_3NO_3 at planting
Spring 2010	Forages regrew	Forages regrew
Summer 2010	Clipped forages in July and forages regrew	Clipped forages in July and forages regrew
Fall 2010	Killed forages on September 10 on S1FP and plowed S1FP on Nov 22.	Plowed S2FP in early Nov.
Spring 2011	Killed forages on June 5; plowed S1SP on June 17; planted soybean with zero fertilizer N input on June 18.	Plowed S2SP on May 20; planted potato and applied 235 N/ha as 56 urea and 180 NH_4NO_3 on May 23.
Summer 2011	Soybean	Potato
Fall 2011	Harvested soybeans on S1FP on October 20 and S1SP on November 10 to 15, respectively.	Top killed on October 4; harvested potatoes on October 17.
Late fall 2011	Not plowed on S1FP and S1SP	Not plowed on S2FP and S2SP
Spring 2012	Planted potato and applied $N = 190$ kg N/ha as NH_4NO_3 on June 18 to 24	Planted barley under-seed with mix of red clover/ryegrass and applied $N = 55$ kg N/ha as NH_3NO_3 on May 3 and 38 kg N/ha as NH_3NO_3 on June 5
Summer 2012	Potato	Barley
Fall 2012	Top killed on September 24; harvested potatoes on October 2 to 6 and 30	Harvested barley on August 19.
Late fall 2012	Not plowed on S1FP and S1SP	Not plowed on S2SP and S2FP and forages regrew
Spring 2013	Barley under-seeded with red clover and applied $N = 60$ kg N/ha as NH_3NO_3	Forages regrew

S1FP = Site 1, fall plowed; S1SP = Site 1, spring plowed; S2FP = Site 2, fall plowed; S2SP = Site 2, spring plowed.

The combination of representative crop rotation sequences, good collaboration from the land owners, and the data from existing monitoring programs within the watershed favored the choice of these sites. Efforts were made to secure more comparable sites within the watershed as replicates without success mainly due to the constraints of resources and site access issues.

Shallow piezometers were installed at the upper and lower ends of the study fields for sampling water to measure nitrate concentration in shallow groundwater. Upper well placement allowed for the characterization of shallow groundwater inflow from the area upgradient of the test fields, while the downgradient wells measured the combined effects of lateral groundwater inflow to, and the vertical drainage from, the spring and fall plowing treatments (Figures 1 and 2). Observations during piezometer construction indicated that the sites are underlain by a red sandstone formation overlain by a layer of glacial till (5 to 13 m at Sites 1 and 5 m at Site 2) (Jiang et al. 2011), in agreement with the regional geology described in the studies by Francis (1989) and Jiang and Somers (2009). The sandstone formation (~1200 to 1600 m) is comprised of a sequence of Permo-Carboniferous terrestrial red beds, consisting primarily of red-brown fine- to medium-grained sandstone, with lesser amounts of siltstone and claystone lenses (van de Poll 1983). Regionally, the bedrock is either flat lying or dipping to the east, northeast or north at an average of 1° to 3° with little structural deformation. Soils derived from the glacial till are sandy, well drained, and relatively uniform across the island (MacDougall et al. 1988).

At Site 1, water levels and lithology observed during piezometer construction indicated that the till acts as a local confining layer, limiting local water interaction between the soil and bedrock aquifer. Thus, water samples from these piezometers could not be used to indicate the effects of plowing treatments in the test fields (Jiang and Somers 2011). Tile drains of 10-cm-diameter perforated polyvinyl chloride (PVC) tubing with spacing of 7 to 25 m were installed by the land owner in 1996 for draining soil moisture for planting purposes in S1SP and a portion of S1FP at a depth of about 85 cm below the surface (Figure 1). Drainage samples from the tile drain outlets (S1WT and S1ET) were utilized to assess the relative effects of plowing treatments on leached nitrate concentrations in S1FP and S1SP respectively (Figure 1) (it is assumed that the variable tile-line spacing would have limited effects on water quality). At Site 2, groundwater flow appears to be controlled mainly by fracture distribution within the bedrock, and the aquifer is unconfined. The piezometers at this location only penetrated to the depth of the first major fracture encountered during drilling, maximizing the likelihood that water samples represent the most immediate effects of drainage and the respective field treatments. Air lifting test was performed when the drilling (an air rotatory drill was used) advanced every 1.5 m in the bed rock and the first major fracture was considered to be exposed if the flow rate increased to 2 to 6 L/s from the borehole. The overburden (i.e., till) was cased off with steel casing with the outside annular space sealed with bentonite in each of the three boreholes. S2NW was completed by installing a 1.5 m section of 2.5 cm diameter

Table 2

Construction Information of Piezometers at Site 2

ID	Date of Drilling	Depth (m)	Steel Casing Depth/ Till Depth (m)	PVC Casing Depth (m)	Screen Depth (m)	Depth of Water Level (m)	Surface Elevation (masl)
S2NW	June 23, 2010	21.6	6.1/4.9	20.1	20.1–21.6	19.5	41.5
S2S1	November 4, 2010	21.3	6.1/5.2	N/A	N/A	16.0	26.2
S2S2	November 4, 2010	23.5	6.1/4.9	N/A	N/A	16.2	25.8

slotted PVC screen in a 2-m-long gravel pack at the bottom, followed by threaded 2.5-cm solid PVC schedule 40 riser to the surface. The gravel pack was isolated from the upper portion of the borehole by emplacing a minimum 2-m bentonite seal above the gravel pack and the remaining annular space was backfilled with drill cuttings and local soil.

S2S1 and S2S2 remain open boreholes. More details about the piezometers are listed in Table 2.

Sampling and Monitoring

Tile-drain effluent was manually sampled at Site 1 at the outlets on a weekly basis during discharging events. Groundwater samples were collected from the piezometers at Site 2 on a monthly basis using Tornado 12V DC submersible pumps. Hourly water levels in the piezometers were recorded using Solinst level loggers. Each piezometer was purged of three borehole volumes before a water sample was collected. In all cases, a 125-mL water sample was collected using a high-density polyethylene bottle. The samples were shipped in coolers with icepacks to the PEI Analytic Laboratories (accredited by Standards Council of Canada) within 24 h and stored in coolers with temperature below 4 °C until analyzed. The samples were analyzed colormetrically for nitrate by flow injection analysis on a Lachat QuikChem 8500 (Lachat Instruments, Loveland, Colorado). Soil bulk density was measured using a 5 cm (high) × 5 cm (wide) cylindrical aluminum core with undisturbed soil samples collected at depths of 0 to 15, 15 to 30 and 30 to 45 cm at six locations in each of the test fields in 2011. Soil samples at the same depths and locations for bulk density test were collected for analyzing soil texture and SOM in 2011. Soil texture was measured using the hydrometer method (Sheldrick and Wang 1993) in 2011. SOM was measured using the loss of ignition method (Schulte and Hopkins 1996). Soil bulk density, texture, and SOM were tested at Holland College in PEI. Above ground forage plant samples were taken prior to herbicidal treatment and plowing to determine biomass, dry matter content, and total C and N by combustion at the PEI Analytic Laboratories.

Coupled LEACHN and MODFLOW Modeling

Nitrate leaching losses were calculated as the product of leached nitrate concentrations below the root zone and soil drainage volumes. Owing to the difficulties of measuring full soil drainage (i.e., the large spacing of tile drains does not allow full interception of drainage water), coupled LEACHN (Hutson 2003), and MODFLOW simulations following a similar approach as in the study by Jiang et al. (2011) were performed to estimate drainage. Briefly, a LEACHN model was developed to predict time series values for daily drainage (i.e., full soil drainage) leaving the soil profile. The model simulated a soil profile of 90 cm with a uniform spatial step of 10 cm. The simulation period covered the period of April 1, 2009 to April 31, 2012 with a uniform time step of 0.1 d. Soil retention properties were estimated using soil texture and SOM data following Rawls and Brakensiek (1985) as described by Hutson (2003). Soil texture and SOM data are listed in Table 3 and were determined through the sampling and test programs discussed in the previous section. Crop data were used to define crop information required for model input. The crop data were based on field records and measurements or estimated by field observations. Meteorological input values (including daily precipitation, maximum/minimum temperature, and snow depth on the ground) were obtained from averaged data obtained from the St. Peters (46°27´1˝N/61°51´18˝W) and East Point (61°51´18˝W/46°27´36˝N) weather stations.

Table 3

Soil Texture and Bulk Density Used in LEACHN

Soil Segment Number	Clay (%)	Silt (%)	Organic Carbon (%)	Bulk Density (kg/dm^3)
1	9.7	35.6	2.2	1.33
2	9.3	35.2	2	1.39
3	8.9	34.7	1.8	1.39
4	9.5	34.3	1.7	1.54
5	10.1	33.8	1.5	1.60
6	13	34	0.2	1.60
7	14	34	0.2	1.79
8	13	35	0.1	1.79
9	14	35	0.1	1.79

A three-dimensional (3D) groundwater flow model was developed using MODFLOW over the entire Souris River watershed. The model has a grid of 168 rows and 262 columns with a uniform spatial step of 50 × 50 m. The upper most portion of the sandstone formation plus the saturated till at a thickness of approximately 180 m is assumed as a transversely anisotropic heterogeneous porous aquifer. Vertically, the aquifer was partitioned into three layers with variable thickness for Layer 1 and a uniform thickness (60 m) for Layers 2 to 3. Initial hydraulic properties were derived from local empirical data (Jiang and Somers 2009). Model boundary conditions were defined following similar approach in the studies by Jiang and Somers (2009) and Jiang et al. (2011).

For steady-state calibration, the model was examined against 20 head measurements within the model domain (i.e., the Souris River watershed) rather than just around the vicinity of the test sites made by the PEI Wildlife Federation (Souris Branch) during 2006 using empirical annual recharge of 420 mm (Francis 1989; Jiang and Somers 2009). LEACHN simulated drainage (Site 1) was then used as recharge for transient groundwater flow simulations. During transient simulations, empirical specific yield and specific storage were used as initial values for model calibration, and water level measurements at the three long-term groundwater level monitoring stations maintained by the Province in the watershed and two locations from this project for the period of April 1, 2009 to March 31, 2010 were used as the calibration target. A trial and error process was utilized to estimate optimal specific yield and specific storage values. The groundwater flow model was then verified against an independent period (April 1, 2010 to March 31, 2012) of measured water levels made at the five stations for transient model calibration.

Nitrate Leaching Estimation

At Site 1, nitrate leaching losses were calculated as the product of simulated drainage and the arithmetic average of the observed tile-drain nitrate concentrations within the period in question. An arithmetic average was used for simplicity, because the tile-drain nitrate concentrations did vary significantly over time except at a few sampling events during low flow periods, which would make a flow weighted mean similar to an arithmetic average. In this study, nitrate leaching losses were only estimated for the forage phase (i.e., the period between May 1, 2010 and June 17, 2011, at which time spring plowing was conducted). The leaching losses before (i.e., Period 1: May 1, 2010 to September 10, 2010) and after (i.e., Period 2: September 11, 2010 to June 17, 2011) the fall herbicidal termination of forage in S1FP were calculated separately. Nitrate leaching losses for the period May 1, 2010 to May 20, 2011 were also calculated to support a comparison of nitrate leaching losses between Sites 1 and 2. The observed nitrate concentrations at tile drain outlets S1WT and S1ET were used to calculate the arithmetic averages of nitrate concentration corresponding to S1FP and S1SP respectively for the two periods. As the field S1SP is located at the lower gradient area of a large wooded area (Figure 1), lateral subsurface flow with low nitrate concentrations from the wooded area could move into drain S1ET, diluting the nitrate concentration leached from field S1SP. Therefore, nitrate leaching from spring plowing treatment with and without dilution correction was calculated separately. The dilution effects in S1FP were considered negligible because the tile drain system in S1FP for water sampling only occupied a small section (3%) of S1FP and is located at the downgradient area of S1FP, and the subsurface flow moving from the larger upper area into the tile drain should have similar water quality to that drained directly from the tile-drained section.

The approach for estimating nitrate leaching at Site 1 could not be applied to Site 2 as no tile drains existed for measuring tile drainage nitrate concentrations. Instead, a mass balance approach based on nitrate concentrations from the piezometers was developed for estimating nitrate leaching for the nonpoint sources. Specifically, nitrate loads leached from the test field were assumed to be equal to the nitrate flux in the lateral groundwater outflow from the test field, minus nitrate flux into the test field from the upgradient groundwater inflow within the upper most portion of the aquifer. It was also assumed that nitrate is transported through the vadose zone within a seasonal time framework and is conservative in the aquifer (Savard et al. 2007). Mathematically, nitrate leaching was calculated as:

$$C_v Q_v = C_{out}(Q_{in} + Q_v) - C_{in}Q_{in} \tag{1}$$

where C_v is average leached nitrate concentration (M/L^3) during the period in question, Q_v and Q_{in} are soil drainage from the test field and upgradient groundwater inflow from outside the field respectively (L^3/T); C_{out} and C_{in} are average nitrate concentrations with groundwater outflow and inflow respectively (M/L^3).

Equation 1 is based on the assumption that the aquifer is stratified, which should hold true because the bedrock hydraulics is dominated by horizontal bedding plane fractures (Francis 1989; Jiang and Somers 2009). Furthermore, the leached nitrate mass is assumed to stay within the upper 5 m of the aquifer (referred to as impacted thickness) because the aquifer is highly transversely anisotropic with horizontal hydraulic conductivity three orders larger than the vertical value (Jiang and Somers 2009). Air lift test during drilling of piezometers suggests that the well yield in the upper 5 m of the aquifer is as low as approximately 3.5 L/s and the horizontal hydraulic conductivity for the section of the aquifer was estimated to be 10^{-5} m/s. The length and width of the test field are 382 and 190 m respectively. Observed nitrate concentrations in S2S1 and S2S2 (Figure 2), representing the combined effects of upgradient lateral groundwater inflow from outside the test field and vertical drainage from spring and fall plowing treatments in the field respectively, were used to define C_{out}. The average nitrate concentration in S2NW was used to define C_{in}. Q_{in} and Q_v were estimated using Darcy's law and LEACHN respectively. Solving the equation produced the nitrate leaching losses. Nitrate leaching losses for the period (Period 1) before fall plowing in S2FP (i.e., May 1, 2010 to November 1, 2010) and the period (Period 2) between post fall plowing in S2FP and prior to spring plowing in S2SP (i.e., November 2, 2010 and May 20, 2011) were estimated separately.

Results and Discussion

Tile-drain and groundwater nitrate concentrations in response to tillage timing.

At Site 1, nitrate concentrations fell between 2 and 6 mg N/L associated with both fields during June to August 2010, prior to herbicidal termination in S1FP (Figure 3). Following the early September 2010 herbicidal treatment of forages in S1FP, associated tile-drain nitrate concentrations rose to 8 to 10 mg N/L, while nitrate concentrations from S1SP intended for spring plowing in 2011 remained at the background levels.

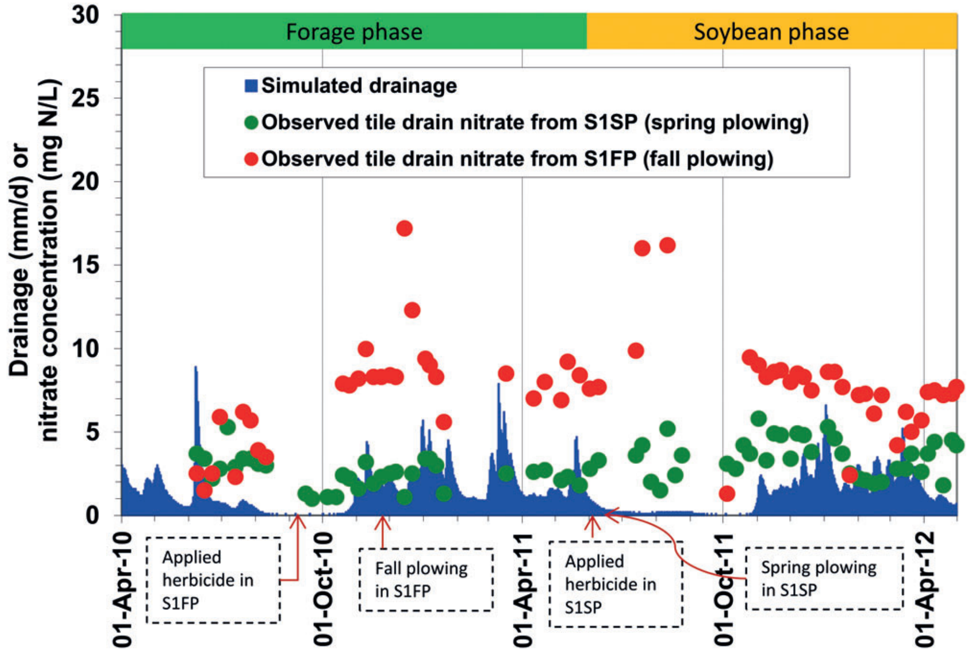

Figure 3. Observed tile drain nitrate concentrations under the fall plowing compared against those under spring plowing to evaluate the effects of tillage timing on nitrate leaching at Site 1.

The tile-drain nitrate concentrations associated with S1FP continued to remain at the elevated levels following fall plowing on S1FP on November 22, 2011 (water samples could not be collected during late August and early September 2010 because of the lack of discharge from tile drains). The tile-drain nitrate concentrations from S1FP continued to remain at the elevated levels after fall plowing on November 22, 2011, and did not increase significantly beyond concentrations observed after herbicidal termination. These results suggest that the elevated nitrate levels from S1FP are primarily associated with effect of the herbicidal termination rather than solely from fall plowing. Forage plant material in S1FP would have been subject to mineralization and nitrification after kill-off, releasing nitrate available for leaching, while forage N in S1FP remained sequestered in the living plant tissue.

Nitrate concentrations following spring plowing and associated herbicidal termination on June 5, 2011 in S1SP also slightly increased but not to the extent observed in S1FP after herbicidal termination for fall plowing (Figure 3). The trend of elevated nitrate levels in the S1FP relative to S1SP extended into the 2011 and 2012 seasons when soybeans and potatoes were planted; the two concentration curves showed a converging trend, but they did not completely converge in the years 2011 and 2012 even though the treatments were similar. This is attributed to the combination of relatively low soil temperature, nitrogen uptake by the soybean crops, and dilution by upgradient lateral subsurface inflow with low nitrate in S1SP. It is postulated that the lateral subsurface flow with low nitrate content from the upgradient wooded area (Figure 2) could move into S1SP when the soil was saturated, diluting the nitrate concentration in the drains. Spring water originated from the north wooded area was observed in a depression a few meters south of the wooded area during the wet seasons, indicating the presence of surface flow. Also, a portion of the spring water could penetrate into the tile before discharging into nearby creek, diluting the nitrate mass in the tile. The water with a forestry origin should have low nitrate level as indicated by the nitrate level in S1NW (<0.02 mg N/L).

Monthly shallow groundwater nitrate concentrations from S2S2 (under fall plowing) were consistently higher than from S2S1 (under spring plowing) during the period between fall plowing in S2FP and spring plowing in S2SP (November 2, 2010 to June 17, 2011) (Figure 4). However, a single data point collected from each of S2S1 and S2S2 before fall plowing was deemed insufficient to judge how nitrate levels under S2FP and S2SP compared prior to fall plowing. Following spring plowing in S2SP in 2011, the associated nitrate concentrations demonstrated an increasing trend, while the concentrations with the fall-plowed field exhibited a decreasing trend; nitrate levels from the two fields converged at the start of the grain season in 2012. The trend of nitrate concentrations from the upgradient piezometer (S2NW), measuring the ground nitrate concentration laterally entering the aquifer from above the area of the test field, remained relatively constant over the whole experimental period. It was noticed that the land use within the recharge area above S2NW did not change significantly during the study period, resulting in little temporal variation of nitrate concentrations in S2NW. These results suggested that the nitrate concentrations from shallow groundwater sampling reflected the effects of the two plowing treatments. Nitrate leaching during the overwinter period and prior to spring plowing was higher in the fall plowed field than in the spring plowed field and nitrate leaching losses appeared to converge to a similar level as the effects of plowing diminished over time. These results also imply that nitrate can move through the vadose zone rapidly, well within a seasonal time framework even

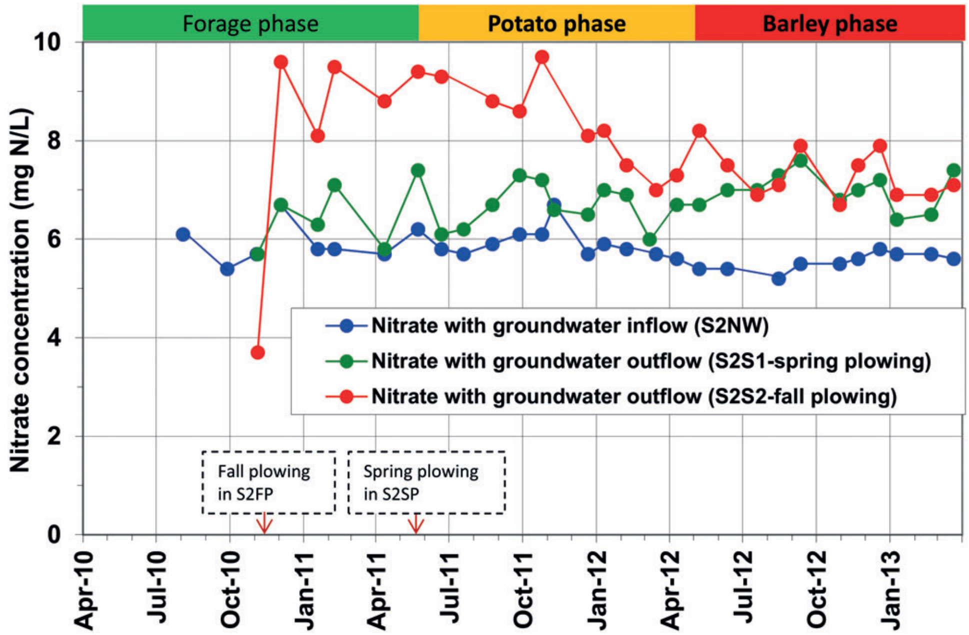

Figure 4. Observed shallow groundwater nitrate concentrations under fall plowing compared against those under spring plowing to evaluate the effects of tillage timing on groundwater nitrate levels at Site 2.

though the water table is 17 to 23 m below the ground surface.

The comparisons between the observed and simulated water levels with daily drainages, predicted by LEACHN as recharge for transient groundwater flow simulations are presented in Figure 5. The simulated timing of increases in water table elevation in S2S1 and S2S2 correlates with the observation well, supporting that the assumption that soil drainage at the depth of 0.9 m reaches the water tables with little lag period at the depth of 16 to 17 m adequately approximates the real field conditions. This is likely attributed to preferential flow in the vadose zone. LEACHN simulations were also performed to further examine the time required for water traveling through the vadose zone (data not presented). Briefly, LEACHN was used to predict drainage occurring below a 10-m vadose zone column in response to precipitation events. For estimating retention properties, it was assumed that the soil properties for 0.9 to 10 m were equal to those between 0.8 and 0.9 m (i.e., clay = 14%, silt = 35%, SOM = 0, and bulk density = 1.8 mg/m^3). The predicted timing of fall drainage at the depth of 10 m was significantly later (~5 months) than the observed rising of water table in response to fall precipitation. This exercise suggests that fall drainage from the root zone has to follow some preferential paths rather than solely through primary porosity represented by soil pores in order to trigger the rising of water table at 16 m below the root zone in the fall. This short time framework is also consistent with the seasonal signals of isotopes identified in wells under similar physical conditions (Savard et al 2007).

Full Soil Drainage Estimation

The model fits of coupled LEACHN and MODFLOW simulations were utilized to measure the reliability of full soil drainage estimation. A comparison between the measured and simulated water levels from steady-state groundwater flow simulation is presented in Figure 6. Note that the water level measurements were made within the overall model domain (i.e., the Souris River watershed) rather than just the adjacent areas of the study sites, and thus encompass a wider elevation range than the study sites alone. The measurements and simulations were correlated with $R^2 = 0.99$ and normalized root mean squared of approximately 5%. Hydraulic conductivities used in the 3D groundwater flow model fell in the ranges used in the models of similar aquifer geology in other watersheds on the island (Jiang and Somers 2009). The fit of transient groundwater flow simulation is illustrated in Figure 5. The simulations matched the observations with a normalized root mean square of 15 to 20%. Greater discrepancy was observed at S2S1 and S2S2, possibly because the heads in the piezometers were point measurements while the simulated heads represented head averages within cells with a dimension of approximately 50 × 50 × 60 m. The specific yield used in the model varied from 0.02 to 0.035, and the specific storage was 2×10^{-5} m^{-1}. Because the specific yield and storage were only adjusted for the period of April 1, 2009 and March 31, 2010, and all the other hydraulic properties were kept unchanged for the remaining period, the simulations between April 1, 2009 and March 31, 2010 and the remaining period could be considered as calibration and verification exercises respectively. Annual full soil drainages were predicted to be 364, 494, and 440 mm for May to April of 2009/2010, 2010/2011, and 2011/2012, respectively. Note that using site-specific soil texture and SOM data, LEACHN predicted similar full soil drainages at both sites, and therefore the full soil drainages were assumed equal at Sites 1 and 2. It was realized that the forages in the fall plowing fields were terminated in the fall, while the forages still remained alive in the spring plowing

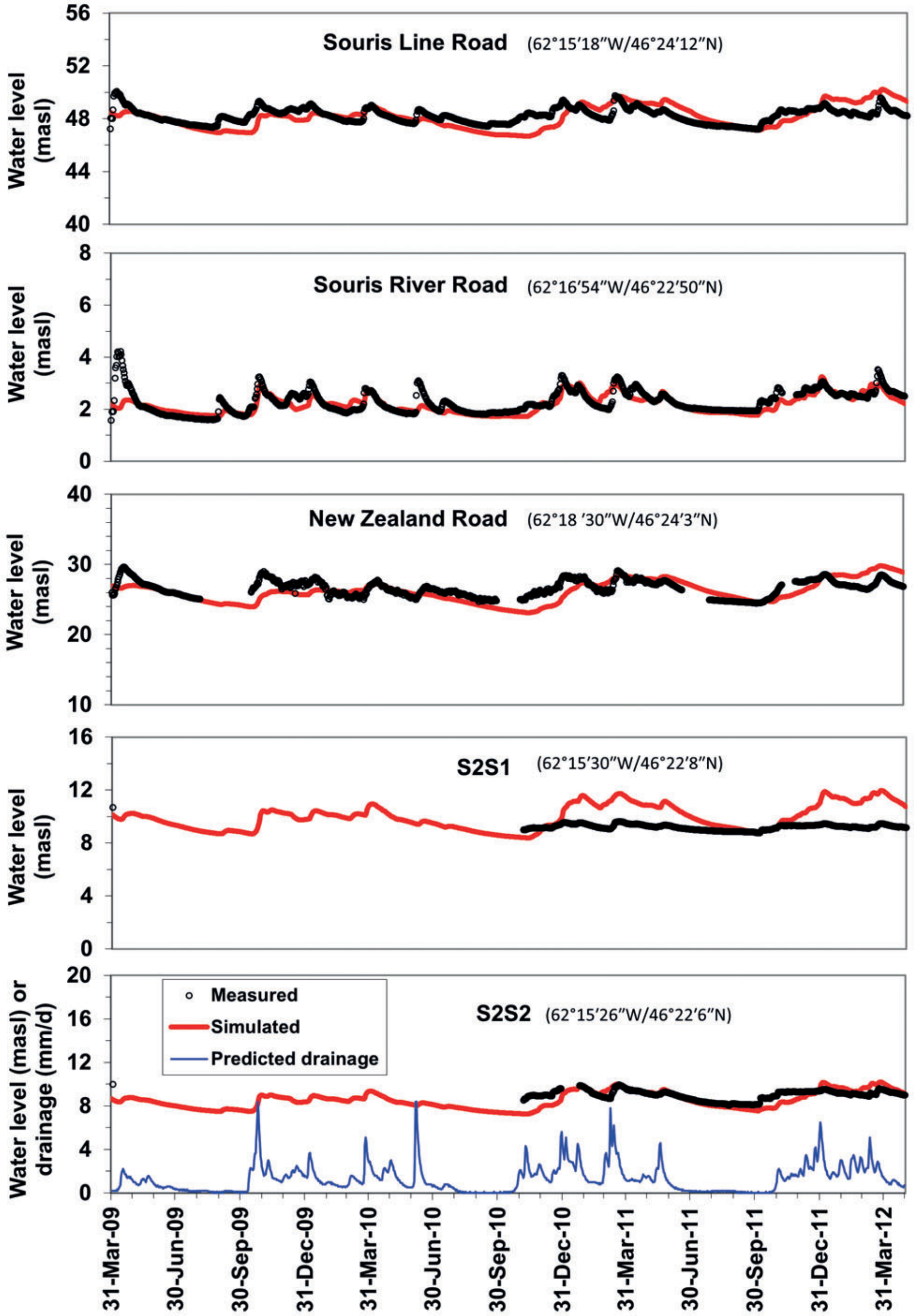

Figure 5. Daily water levels predicted by MODFLOW using daily drainage predicted by LEACHN as recharge, compared against observations to evaluate the correlation between observed rising of water table and predicted occurrence of drainage, and the performance of LEACHN in predicting drainage (the locations of the monitoring wells at New Zealand Road, Souris Line Road, and Souris River Road are within the groundwater flow domain but outside of the site maps as showed in Figures 1 and 2).

fields, which could result in drainage differences between the two treatments because of differences in evapotranspiration and soil surface texture. However, the ET effects were considered negligible because the ET was much lower in the offseason than in the growing season (Jiang et al. 2012). These predicted full soil drainages were very close to the empirical recharge values in PEI reported by Francis (1989). The coupled modeling exercises suggest that the simulated full soil drainage could be used as an alternative for estimating nitrate leaching in the absence of full soil drainage measurements.

Nitrate Leaching Losses

Estimated forage-phase nitrate leaching losses for different periods at Site 1 are listed in Table 4. Nitrate leaching from the fall-plowed fields (S1FP) was higher than from the spring-plowed field (S1SP) based on the higher tile-drain nitrate concentrations from S1FP compared with those from S1SP, and the assumption that drainage volumes were equal for both fields. Treating that the soils in S1FP and S1SP are identical (soil texture and SOM data indicate so), and non-diluted nitrate concentrations in the east tile (S1ET) equaled to the nitrate concentrations (averaged at 4.15 mg N/L) in

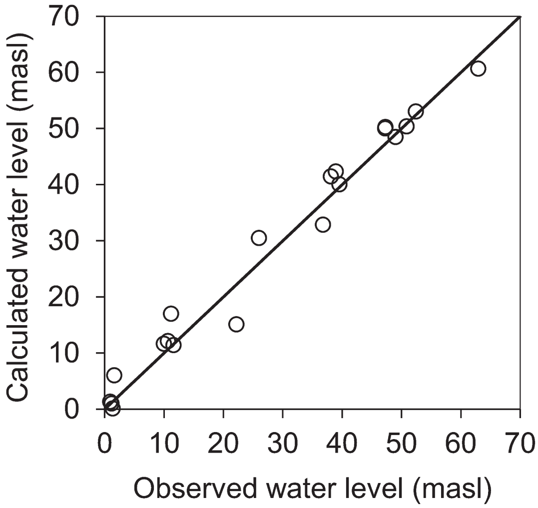

Figure 6. Comparison between calculated and observed water levels to evaluate the performance of steady-state groundwater flow model.

the west tile (S1WT) before herbicidal termination in S1FP and did not vary significantly over time before spring plowing in S1SP. The non-diluted nitrate leaching from S1SP was calculated as 19.8 kg N/ha by multiplying the non-diluted nitrate concentration averaged by the corresponding drainage (i.e., 477 mm) during this period. The dominant portion of the leached nitrate from S1SP likely originated from SOM mineralization, since the forage plants in this field remained alive before spring plowing and the contribution from the atmospheric sources was low given annual wet N plus dry N atmospheric deposits as low as 3.7 kg N/ha with an error of 30 to 50% (R. Vet, personal communication, 2005). If nitrate leached from S1SP was assumed to originate exclusively from SOM mineralization, net nitrate leaching due to mineralization of the fall plow-down forages would be 18.4 to 25.8 kg N/ha. These values represented the forage-phase (May 1, 2010 to May 20, 2011) nitrate leaching reduction (44 to 61%) due to delaying plowing forages and/or associated herbicidal treatment from fall to spring. The presence of tile drains could accelerate water movement in the soil and alter the hydraulic conditions of the soil, and thus change the fate/transport and transformation of N in the soil. However, the tile drain spacing is fairly large (7 to 25 m) in a sandy soil, and some random tile-drain discharge measurements indicated that the tile drainage was much lower than the empirical recharge and LEACHN-simulated drainage. Thus, the tile-drain samples are considered to approximately represent the in situ soil conditions.

Estimated forage-phase nitrate leaching losses at Site 2 are presented in Table 5. Forage-phase nitrate leaching

Table 4

Forage-Phase Nitrate Leaching Losses at Site 1

	Drainage (mm)	S1FP C^1_{out} (mg N/L)/ Leaching (kg N/ha)	S1SP C^1_{out} (mg N/L)/ Leaching (kg N/ha)	S1SP C^1_{out} (mg N/L)/Leaching (kg N/ha) (Dilution-Corrected)
Period 1: May 1 to September 18, 2010 (before herbicidal termination)	127	4.15/5.3	3.0/3.8	4.15/5.3
Period 2: September 19, 2010 to June 17, 2011 (after herbicidal termination and before spring plowing)	477	8.2/39.1	2.8/13.3	4.15/19.8
May 1, 2010 to June 17, 2011	604	4.15–8.2/44.4	3.0–2.8/17.1	
May 1, 2010 to May 20, 2011	575	4.15–8.2/41.9	3.0–2.8/16.1	4.15/23.5
Leaching from soil organic matter	—	16.1–23.5	3.0–2.8/16.1	4.15/23.5
Leaching from forages	—	25.8–18.4	0	0

[1]C_{out} = arithmetic average of tile-drain nitrate concentration.

Table 5

Forage-Phase Nitrate Leaching Losses at Site 2

	Q_{in} (m^3/d)	C_{in} (mg N/L)	Q_V (m^3/d)	S2FP C^1_{out} (mg N/L) / Leaching (kg N/ha)	S2SP C^1_{out} (mg N/L)/ Leaching (kg N/ha)
Period 1: May 1 to November 1, 2011 (before fall plowing)	12.3	6.0	26.7	6.8/9.8	6.8/9.8
Period 2: November 2 to May 20, 2011 (after fall plowing and before spring plowing)	12.3	6.0	79.3	8.8/40.7	6.8/30.5
May 1, 2010 to May 20, 2011	12.3	6.0	26.7–79.3	6.8–8.8/50.5	6.8/40.3
Leaching from soil organic matter	—	—	—	40.3	40.3
Leaching from forages	—	—	—	10.2	0

Q_{in} = upgradient lateral groundwater inflow rate; C_{in} = nitrate concentration in upgradient lateral groundwater inflow; Q_v = soil drainage rate; S2FP = Site 2, fall plowed; S2SP = Site 2, spring plowed.
[1]C_{out} = nitrate concentration in downgradient lateral groundwater outflow.

losses from S2FP were 20% higher than that from S2SP. Similar to Site 1, if the nitrate leaching from S2SP was assumed to originate solely from SOM mineralization, net nitrate leaching derived from fall plow-down forages would be 10.2 kg N/ha. This provides an indication of the magnitude of the net reduction in nitrate leaching due to delaying forage plowing from fall to spring. The net nitrate leaching due to fall forage plow down could vary from 9 to 22 kg N/ha if the hydraulic conductivity varied from 10^{-6} to 10^{-4} m/s or the impacted thickness of aquifer from 3 to 30 m, suggesting that estimation is not highly sensitive to the variation of the less certain parameters.

The nitrate leaching derived from the plowed/killed forages at Site 1 was as much as twice at Site 2 (18.4 to 25.8 vs. 10.2 kg N/ha) during the comparable period. This was likely partially owing to the combination of the early fall herbicidal termination and lower C/N ratio (20 and 27 at Sites 1 and 2 respectively) with the forages at Site 1, although other factors, such as the differences of sites and assessment approaches, could contribute to the difference. Early fall herbicidal termination kills the forages within a short period of time stimulating a fast crop residue decomposition when soil moisture and temperature are favorable for mineralization (i.e., the earlier herbicide is applied, the more nitrate leaching would be created), while lower C/N could accelerate the decay process (Hutson 2003). Soil sampling indicated that soil nitrate contents in S1FP were significantly elevated over the S1SP at Site 1 upon the fall forage termination in S1FP (data not presented). These findings were consistent with the soil-based data reported by Sanderson et al. (1999). The nitrate leaching losses from SOM mineralization at Site 2 (40.3 kg N/ha) were estimated to be higher than at Site 1 (16.1-23.5 kg N/ha) for the comparable period. This was likely because of the differences of the soils and plants between the two sites and partially to the uncertainties with the estimations.

The weather conditions in the summer and fall of 2010 are expected to influence the forage growth and the decay of the plow down forages and SOM. The summer (June to August) and fall (September to November) precipitation (summer 425 mm and fall 425 mm) in 2010 were higher than the multiple year averages (summer 266 mm and fall 315 mm) based on the data from the Charlottetown airport weather station. While the summer temperature in 2010 was at the normal level, the fall temperature was about 1 °C higher than normal. The higher than normal moisture and temperature levels in 2010 are expected to favor the forage growth and soil mineralization processes, and as a result, the estimated nitrate leaching losses are likely higher than those under more typical weather conditions.

Decay Ratio of Fall-Plowed Forages

At Site 1, N accumulation in the forage plants was determined to be 85 kg N/ha based on aboveground plant tissue sampling prior to pre-plow herbicidal termination in the fall of 2010. Nitrogen accumulation in the whole plants was estimated to be 115 kg N/ha, assuming root N accumulation at 30 kg N/ha based on Bolinder et al. (2002). Following similar sampling and calculation procedures as used at Site 1, N accumulation in forage plants prior to fall plowing at Site 2 was estimated to be 106 kg N/ha. On the basis of this, the net nitrate leaching derived from the fall herbicidal termination and associated fall plowing at Site 1 accounted for 16 to 22% of the total amount of N in the plow-down forages. At Site 2, the net nitrate leaching derived from fall-plowed forages accounted for 9.6% of the total amount of N in the forage plants. While this suggests postponing plowing forages and associated herbicidal termination from fall to spring could reduce nitrate leaching losses during the non-growing season, the amount of N released during this period was relatively small compared to the overall N content in the forage plants in both treatments. A large portion of N in the plow-down forages remained in the soil until the following season or seasons, providing opportunities for crediting the carried-over soil N for the subsequent crops. Thus, growers should consider accounting for soil N supply for succeeding crops even if they conduct fall plowing. How much N can be credited from soil N supply largely depends on weather conditions, SOM level and quality, tillage practices, and is an ongoing research topic of interest.

Economic Implications of Fall vs. Spring Plowing

Respective soybean yields, for crops planted after the fall/spring plowing trials, were reported to be 1.48 and 1.98 T/ha on S1FP and S1SP in 2011 by the grower. While there were not sufficient data to conduct statistical analysis on the yields, the difference on the yields likely resulted from the different varieties planted on the test fields. The potato yields were reported to be 41.3 T/ha on the S2FP and S2SP test fields in 2011 without noticeable differences on yields and quality. This suggested that the crop yields and quality were similar under the two tillage timings. However, implementing spring plowing incurred additional logistical challenges for the growers in relation to field preparations on the land during the busy planting season, although these additional costs were not quantified. More research is needed on quantifying the extent to which the reduction of fertilizer N costs due to spring plowing could offset the additional costs of logistical challenges due to spring plowing.

General Applicability of the Results

The assessments were based on data from one cycle of a 3-year rotation at two separate sites and some assumptions were necessary in estimating nitrate leaching, and subsequently, included some uncertainties. Although the nitrate leaching estimations included some uncertainties, the nitrate reduction trends due to implementing spring plowing observed through this study are certain and consistent with former soil-based results (Sanderson et al. 1999; Sanderson and Macleod 2002). The tests were undertaken at commercial operations in fields that are significantly larger than typical research plots and thus, the results probably reflect the conditions of commercial operations better. The geology, soil, and weather are relatively uniform in PEI (MacDougall et al. 1988; van de Poll 1983), and the management practices associated with potato production in PEI were assumed to be similar because most of the growers supplied their potatoes to the local French fry processing plants and they were required to follow similar production standards. Thus, the major controls of the nitrate leaching losses in the off-site fields in PEI are probably similar to those discussed in this study, and therefore, the results should be applicable island wide. Similar potato production practices are followed under similar weather and soil conditions in many areas in eastern North America (Zebarth and Rosen 2007), and thus the results are likely applicable to these areas as well. Data from another cycle of a 3-year rotation could help validate the results and provide additional confidence by industry in the value of implementing these practices.

Conclusions

At Site 1, fall plowing resulted in elevated tile-drain nitrate concentrations compared to spring plowing probably due to pre-plow herbicidal termination of the fall-plowed field and to a less extent potential dilution effects by subsurface inflow with low nitrate in the spring-plowed field. A similar trend was also observed during forage phase regarding shallow groundwater nitrate concentrations at Site 2. Respective nitrate leaching losses during the forage phase (i.e., May 1, 2010 to May 20, 2011) from the fall vs. spring plowed fields were estimated to be 41.9 vs. 16.1 to 23.2 kg N/ha and 50.5 vs. 40.3 kg N/ha at Sites 1 and 2 (i.e., 20 to 61% reduction). The practice of delaying forage plowing and/or associated herbicidal termination until spring reduced the magnitude of nitrate leaching without compromising crop yields and quality in the following season. Thus, spring plowing of forage crops should be encouraged for nitrate mitigation in PEI. However, if due to logistical reasons, fall plowing is implemented, growers should consider postponing the plowing operations as late as possible and abandoning fall pre-plowing herbicidal termination to minimize nitrate leaching losses during the offseason.

The nitrate leaching losses derived from the mineralization of the killed or/and plow-down forages were estimated to account for 16 to 22 and 9.6% of the overall N accumulated in the forage plants at Sites 1 and 2, respectively. This indicates that a small fraction of the fall plow-down forages decayed during the forage phase and a large portion was integrated into the soil as SOM even if fall plowing was adopted. Growers should therefore consider accounting for soil N supply regardless of fall or spring tillage practices. Further studies are needed to quantify the capacities of soil N supply for subsequent crops under fall and spring plowing practices.

The effects of inter-annual weather on nitrate leaching were not accounted for in the assessments. The assessments were based on data from one season as part of a 3-year rotation and subject to some uncertainties.

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