Chapter 13
Nitrate Leaching from Potato Production in Eastern Canada

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Abstract Nitrate leaching from potato production systems is of economic importance, and also of concern for both drinking water quality and the health of aquatic ecosystems. We examine the processes, timing and magnitude of nitrate leaching, and examine practices developed to reduce nitrate leaching from potato production systems, with a particular focus on Prince Edward Island. Results from tile-drain experiments indicate that nitrate leaching occurs primarily during late autumn winter and early spring when crop uptake diminishes, and elevated nitrate concentrations coexist with water movement from the root zone, with the timing of nitrate leaching generally corresponding with major recharge events. Based on stable isotopic signatures, nitrate leached during the growing season is primarily from mineral fertilizers and mineralization of soil organic N whereas nitrate leached outside of the growing season

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originates primarily from mineralized N (including microbially-modified fertilizer N). Nitrate concentrations in tile-drain water from potato plots were commonly above the 10 mg NO_3-N L^{-1} drinking water quality guideline, and were higher from potatoes than from red clover or cereal plots. Simulations using LEACHN predicted that >80% of nitrate leaching occurred outside of the growing season, a finding consistent with water balance calculations in intensively cultivated watersheds. Nitrate leaching under conventional potato-barley-red clover rotations were predicted to be 27–91 kg N ha^{-1} (average 56 kg N ha^{-1}), corresponding to concentrations of nitrate in drainage of 5.6–18 mg N L^{-1} (average 10.7 mg N L^{-1}). Nitrate leaching was predicted to increase with fertilizer N rate for potato, and decreased with rotation length. Nitrate leaching can be reduced through implementation of practices which reduce the accumulation of nitrate in the root zone, particularly at potato harvest. These practices may include improved crediting of soil N mineralization from soil organic matter and crop residues, use of in-season measures of crop N status to guide in-season N management, and introducing potato cultivars with lower fertilizer N requirements or higher N use efficiency. The requirement for high N inputs to obtain economic tuber yields, in combination with the high risk of nitrate loss from the root zone, present significant challenges to growers with respect to N management. Reducing the frequency of potato in the crop rotation, and use of practices to reduce residual nitrate in potato production, will be most effective in reducing nitrate leaching losses.

13.1 Introduction

Nitrogen (N) losses to groundwater from agricultural production systems are a common environmental issue world-wide (Power and Schepers 1989; Spalding and Exner 1993; Böhlke 2002). In agricultural settings, nitrate leached below the crop root zone can impair the quality of underlying groundwater (Nolan et al. 2002; McMahon et al. 2007; Puckett et al. 2011). In addition, the discharge of nitrate-enriched groundwater as base flow delivers high loads of N to surface waters, which impair aquatic ecosystems (Mitsch et al. 1999; Keith and Zhang 2004).

High concentrations of nitrate are of concern for drinking water quality, and drinking water guidelines for nitrate are commonly set at 10 mg NO_3-N L^{-1} (United States Environmental Protection Agency 2009; Health Canada 2010). High nitrate concentrations are also of concern in fresh surface waters and in estuarine environments and may contribute to eutrophication and deterioration of aquatic habitat (Pionke and Urban 1985; Bachman et al. 1998). In Canada, the guideline for the protection of freshwater aquatic habitat is 2.9 mg NO_3-N L^{-1} (CCME 2003). Thus, N losses from agricultural production systems are of concern both for drinking water quality and the health of aquatic ecosystems.

Nitrogen is the nutrient required in the largest quantities for crop growth and almost all non-leguminous crops need N inputs as mineral or organic fertilizer or biological N fixation for optimal production. Agricultural systems are, however, inherently "leaky", and a certain amount of N within the system is subject to losses. Given the important role of N in crop production, these N losses can also have important economic as well as environmental implications. Nitrate leaching is a major pathway for N loss in humid regions and in irrigated agricultural systems (Jemison and Fox 1994; Baker 2001).

Nitrate leaching losses from potato (*Solanum tuberosum* L.) production are of particular concern, and there is evidence of increased groundwater nitrate contamination associated with potato production (Hill 1986; Richards et al. 1990; Benson et al. 2006). The potato crop usually receives high fertilizer N inputs in order to meet industry tuber yield and size requirements (Zebarth and Rosen 2007), whereas apparent recovery of applied fertilizer N in the potato crop commonly ranges from 40–60% in Eastern Canada (Zebarth and Rosen 2007) and Western Europe (Vos 2009). In drier regions, where not all nitrate lost from the root zone over the winter period, the risk of nitrate leaching losses may be reduced by growing potatoes in rotation with deeper-rooted crops, such as barley (Delgado et al. 1999, 2001b; Dabney et al. 2001). Estimates of nitrate leaching losses from commercial potato fields in Eastern Canada ranged from 10–171 kg N ha^{-1} (Milburn et al. 1990; Gasser et al. 2002). Nitrate concentrations in leachate from potato fields commonly exceed the 10 mg NO_3-N L^{-1} drinking water guideline for nitrate (Milburn et al. 1990; Vos and van der Putten 2004).

This chapter examines nitrate leaching from rain-fed potato production in Eastern Canada, and considers the effects of climatic conditions, soil properties and management practices in influencing nitrate leaching. The chapter has a primary focus on potato production in Prince Edward Island (PEI), and uses specific examples of work done in PEI to illustrate these controls on the leaching process.

13.2 Groundwater Nitrate Contamination in PEI

PEI is the smallest province in Canada, yet it produces about one fourth of the Canadian potato crop (Statistics 2009). Agricultural land accounts for 40% of the island's land mass, about half of which is in potato rotations. Potatoes are commonly grown in a 3-year rotation with barley (*Hordeum vulgare* L.) and forage crops (red clover (*Trifolium pratense* L.) or mixture of red clover and perennial grasses such as timothy (*Phleum pratense* L.)). Russet Burbank is the main cultivar grown, and the main market for the potato crop is for processing (French fry) purposes. Barley is grown primarily for livestock feed. Traditionally the forage crops were grown in a system where the forage was harvested mid-season for animal feed and ploughed down at the end of the growing season as a green manure. Inclusion of forage crops, particularly legumes, in potato rotations are important in maintaining the productivity of these low organic matter soils (Stark and Porter 2005).

PEI has a cool maritime climate, humid soil moisture regimes, cool wet spring conditions and short growing seasons. The short growing season limits the potential for use of cover crops to take up residual nitrate after potato harvest, and most nitrate is lost from the root zone over the winter period (Zebarth et al. 2009).

The soils used for potato production were derived from continental glacial till and are sandy and well-drained, however subsoils may be prone to compaction and have low soil pH, and consequently root penetration is frequently limited. The soils are underlain by an unconfined and semi-confined fractured-porous sandstone aquifer, which supplies all of the drinking water, and a large majority of industrial water and base flow to freshwater streams, on the island.

The combination of a humid climate, sandy soils and intensive potato production systems over an unconfined and semi-confined aquifer creates a favourable situation for nitrate leaching in PEI. As a result, groundwater nitrate contamination is prevalent. Nitrate concentrations in well water in PEI averaged 3.7 mg NO_3-N L^{-1}, which is 2 to 3 mg NO_3-N L^{-1} higher than background groundwater nitrate concentrations (Jiang and Somers 2009). In addition, 15–20% of domestic wells had nitrate concentrations above the 10 mg NO_3-N L^{-1} drinking water guideline in watersheds with a large proportion of land in potato production (Jiang and Somers 2009).

Nitrate-enriched groundwater discharged to the local streams and associated estuaries has been suggested as one of the factors implicated with the anoxia events prevailing in some estuaries in PEI (Young et al. 2002). Isotopic analyses of nitrate in groundwater and surface waters of the Wilmot River watershed show essentially identical characteristics suggesting base flow is a primary source of the nitrate in surface waters (Savard et al. 2007). Island-wide monitoring data indicates that nitrate concentrations of stream water have increased over time, and in some cases have increased several-fold since the 1960s (Somers 1998). Isotopes of nitrate in both groundwater and surface water in the Wilmot River watershed in PEI suggest that nitrate originates in approximately equal proportions from mineral fertilizers and from soil organic materials during the growing season, whereas outside of the growing season, N was derived primarily from soil organic N (including microbially-modified fertilizer N) (Savard et al. 2010).

13.3 Controls on Nitrate Leaching from Potato Production

Nitrate leaching occurs when moving water and nitrate coexist in the soil (Meisinger and Delgado 2002). The movement of water, and thus nitrate, below the root zone occurs when precipitation rate or irrigation exceeds the evapo-transpiration rate and soil water content exceeds field capacity. The quantity of nitrate in the soil which is available for leaching depends on the complex interaction of several processes in the C (carbon) and N cycles. These processes and transformations that control nitrate availability occur simultaneously with nitrate transport within the soil profile. The net effect of these processes, and thus the potential for nitrate leaching from the root zone to groundwater, depends on climatic conditions, soil properties and management practices.

13.3.1 Soil and Climatic Controls on Water Movement

Soil and climatic conditions play an important role in influencing the amount of drainage. Irrigation is limited in PEI, and consequently precipitation and evapo-transpiration are the primary factors that influence the magnitude and timing of drainage.

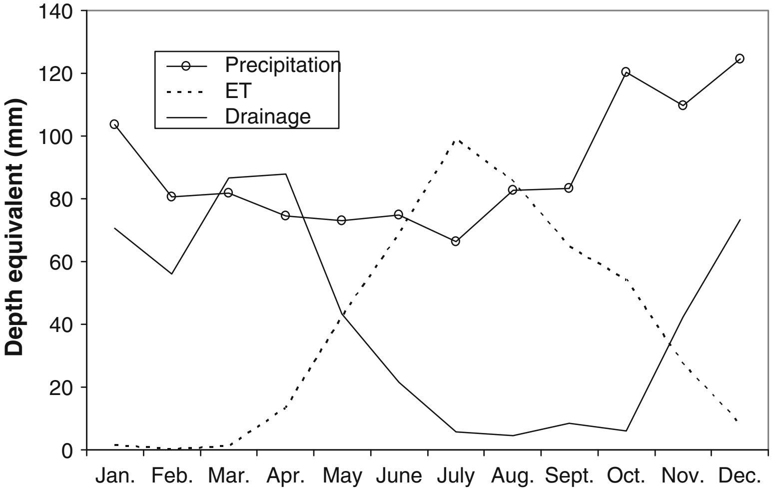

Fig. 13.1 Monthly precipitation, drainage and evapo-transpiration (ET) from a typical potato production system in PEI with a barley-red clover-potato rotation averaged over the period 2000–2008. Drainage and ET values are based on LEACHN predictions using Charlottetown soil series information and climate data from the Environment Canada weather station at the Charlottetown Airport

Timing of drainage is illustrated by a simulation (Jiang et al. 2011) performed using LEACHN (Hutson 2003) for a potato production system for the period 2000–2008 (Fig. 13.1). Average annual precipitation during this period (1075 mm) was very close to the long-term average (1100 mm). Average annual evapo-transpiration and drainage were predicted to be 416 and 506 mm, respectively. Drainage in March and April was predicted to be greater than precipitation due to snowmelt. It was predicted that 82% of the drainage occurred from November to April, emphasizing that most drainage occurs outside of the May to October growing season. Monthly evapo-transpiration was similar to or exceeded precipitation from June to September, and consequently drainage during this time would primarily occur in response to significant rainfall events.

These simulations are consistent with results from tile-drain experiments in PEI and New Brunswick. High tile-drainage effluent discharges were measured during the October to April period and near zero or very limited drainage effluent was measured during the May to September period (Milburn et al. 1990, 1997). The simulations are also consistent with the response of shallow water table and stream discharge to recharge events on PEI. For example, water table elevations at Sleepy Hollow monitoring well near Charlottetown generally increased in spring over the March to May period each year in response to snowmelt recharge events and declined over the June to October period when evapo-transpiration exceeded precipitation and net drainage (i.e. recharge) was limited (Fig. 13.2). The water table elevation subsequently increased over the November to February period because evapo-transpiration diminished and net drainage from snowmelt and/or rainfall infiltration recharged the water table. Similar responses can be observed at the other

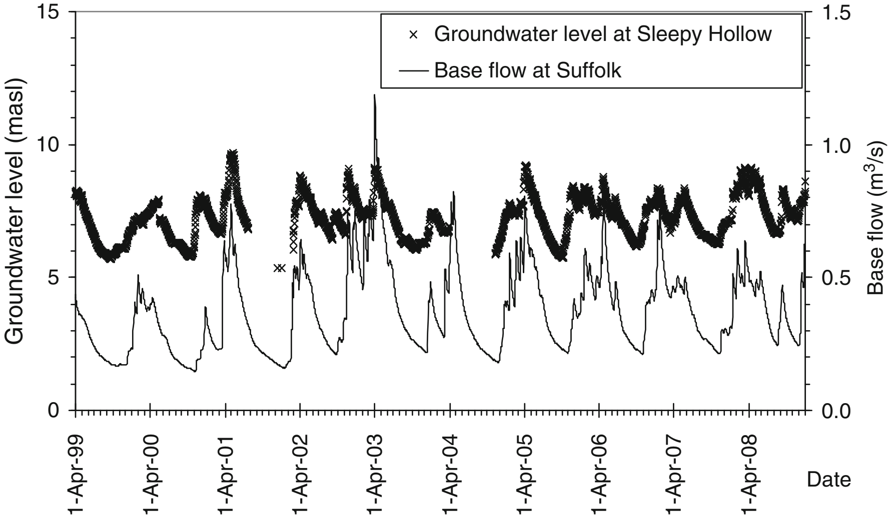

Fig. 13.2 Daily groundwater level elevation (masl-meters above sea level) and base flow (separated from measured stream discharges) from Sleepy Hollow and Suffolk PEI, respectively. Recharge in late autumn winter and spring are reflected in both groundwater level elevations and base flow

shallow monitoring wells on the island (PEIEEF 2011). The calculated base flows at Suffolk (Fig. 13.2), as well at the other hydrometric stations on PEI, demonstrate similar seasonal rising and falling responses.

Nitrate leaching is also influenced by soil properties. The risk of leaching is increased in sandy soils and soils with low organic matter content due to reduced soil water holding capacity. In coarse-textured soils, water infiltration due to rainfall events can rapidly move nitrate below the surface soil, where it is no longer accessible to the growing crop. Shallow unconfined aquifers underlying sandy soils are particularly vulnerable to nitrate contamination (Dubrovsky and Hamilton 2010). Soils in PEI are commonly sandy and have relatively low (15 to 35 $\mathrm{g\,kg^{-1}}$) organic matter content, which favours nitrate leaching. Elevated nitrate in the underlying shallow unconfined aquifer was highly spatially correlated with intensity of potato cropping (Benson et al. 2006).

In a 2 year geochemical study in the Wilmot River watershed of PEI, a strong seasonal association was observed between $\delta^{18}O$ ratios (i.e. the ratio of $^{18}O/^{16}O$ in water samples compared with the standard) in precipitation and in nitrate dissolved in shallow groundwater samples. The relationship has as its basis in the approximation that during nitrification, two-thirds of the oxygen incorporated into the nitrate molecule is from soil water, bearing the isotopic characteristics of recent precipitation, and one-third is from the atmosphere with a constant $\delta^{18}O$ ratio (Snider et al. 2010). The seasonally distinct $\delta^{18}O$ ratios in nitrate observed in shallow groundwater therefore provide a geochemical marker for the timing of nitrification and of recharge to the aquifer. Combined with estimated daily recharge rates, these results indicate that winter and spring periods provide high rates of N transfer to the aquifer relative to the growing season (Savard et al. 2007).

It is important to have information on the magnitude and timing of leaching from the root zone, however direct measurement of leaching from the root zone to the underlying groundwater is a challenging task (Powlson 1993). Tile drain effluent has been used by some researchers to estimate leaching (Jemison and Fox 1994), however this may significantly underestimate recharge. For example, annual tile drainage was reported to be 86 to 132 mm yr^{-1} in PEI during 1989–1992 (Milburn et al. 1997) whereas annual recharge during the same time period was estimated to be as high as 310–490 mm yr^{-1} during the same timer period using a local empirical recharge coefficient of 30–40% of annual precipitation (Francis 1989) and annual precipitation of 1056–1232 mm for the same period. This suggests that a large proportion of recharge may bypass the tile-drain systems.

Crude approximations of N fluxes may be made at a watershed scale, and have been used for the Wilmot River watershed to estimate the relative magnitude of N delivered to the aquifer during the growing and non-growing seasons (Somers and Savard 2008). Combining daily recharge rates determined using the approach of Healy and Cook (2002) and seasonal groundwater nitrate concentrations, N flux to the aquifer is estimated to be 25% during the growing season and 75% during the non-growing season.

The potential to estimate leaching through water balance calculations is limited because not all terms within the water balance equation can be readily and accurately characterized (Itier and Brunet 1996). Consequently, because of the many physical, chemical and biological processes affecting leaching, simulation models are commonly used to predict leaching (Addiscott and Whitmore 1991). Many process-based models have been developed to simulate nitrate leaching below the crop root zone as a function of soil properties, climatic conditions and management practices. Examples of these include SOILN (Johnsson et al. 1987), LEACHM (Wagenet and Hutson 1989; Hutson 2003), NLEAP (Shaffer et al. 1991) and HYDRUS (Simunek et al. 2008). Most of the models are one dimensional and subsequently do not capture the heterogeneities (especially in the horizontal extent) in soil, climate, management and topography. These models commonly require site-specific soil and climate data and management-specific data as input, and many of the data were not collected in the field if model calibration was not the major intent. Lack of input data creates a barrier for their practical application to agricultural systems (Shaffer 1995).

13.3.2 Soil, Climatic and Management Controls on Nitrate Availability

Soil nitrate originates primarily from mineral fertilizers, organic amendments, crop residues, biological N fixation and soil organic matter. Soil nitrate present in the soil may be taken up by plants, assimilated by soil microorganisms, or lost to the atmosphere by denitrification. The balance between these processes controls the availability of nitrate in soil which has the potential to be lost by leaching.

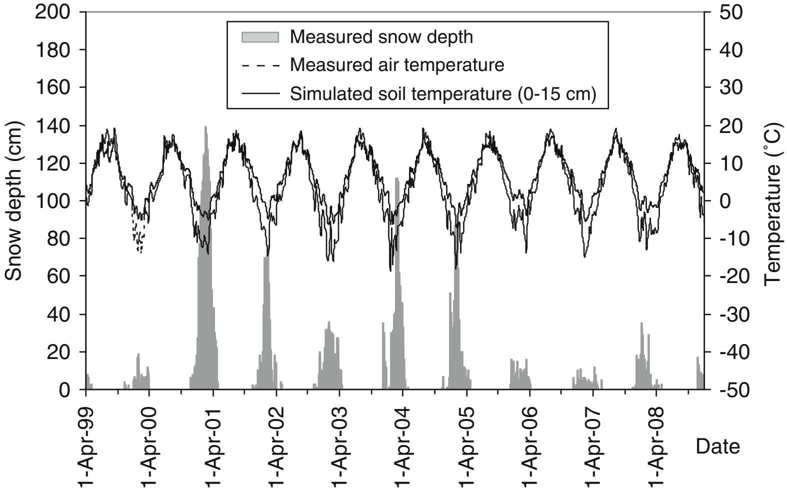

Fig. 13.3 Seasonal variation in soil temperature and drainage simulated using LEACHN and using observed air temperature and snow depth at the Charlottetown Airport, PEI

The mineralization of organic N in soil is controlled primarily by the amount and quality of soil mineralizable N and environmental conditions, primarily soil temperature and water content (Zebarth et al. 2009). Soil mineralizable N is influenced by organic amendment use (Sharifi et al. 2008a), addition of crop residues (Sharifi et al. 2009), tillage (Sharifi et al. 2008b), soil properties and climatic zone (Dessureault-Rompré et al. 2010). The C/N ratio, composition and particle size of crop residues affect the mineralization process (Kumar and Goh 2000).

Soil temperature and water content control rates of microbial growth and activity, and consequently influence the processes of mineralization, nitrification and denitrification (Johnsson et al. 1987; Hutson 2003). Therefore climate, and the annual variations in climatic conditions, influences both the availability of nitrate for leaching and the potential for leaching to occur. Most microbial activity occurs under warmer soil temperatures during the growing season. However, it is common for soils to remain unfrozen over much of the winter period. For example, simulated soil temperatures for 0–15 cm depth could be above zero for much of the late autumn winter and spring despite some sub-zero air temperatures (Fig. 13.3). As a result, soil N and C cycling can occur, albeit at a slower rate, outside of the crop growing season.

An isotopic approach was used to investigate N dynamics at a watershed scale, and to quantify seasonal N fluxes to groundwater in the Wilmot River watershed in PEI. Land use in the watershed is predominantly agricultural (74% of total land area) dominated by potato production. As such it provides a good example of the impact of intensive potato production on water resources at a watershed scale. A source apportionment model was developed using δ^{15}N and δ^{18}O ratios in groundwater and for principle N sources (manure and sewage, inorganic fertilizers and

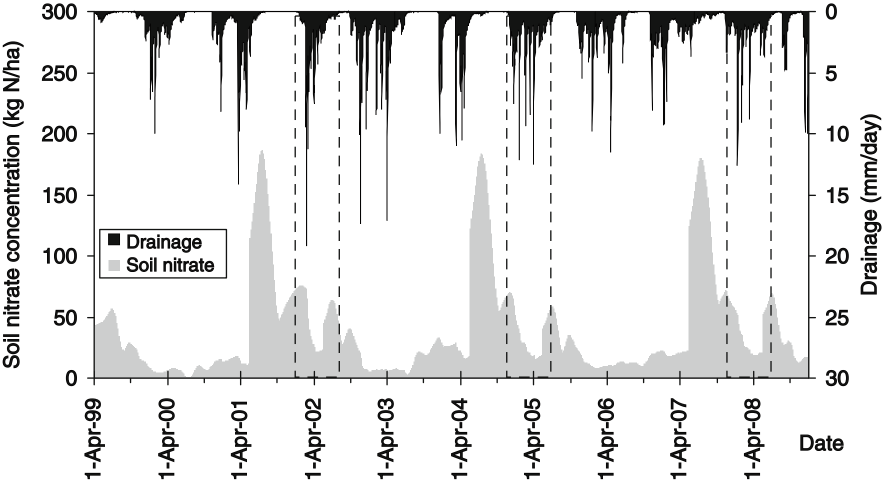

Fig. 13.4 Soil nitrate concentration and drainage under a conventional barley-red clover-potato production system in PEI simulated using LEACHN. A potato crop was present in 2001, 2004 and 2007 (The dash boxes highlight the periods of high nitrate leaching risk where potatoes are harvested, and high soil nitrate concentration and drainage coexist)

soil organic matter) (Savard et al. 2010). It was concluded that nitrate loading to groundwater during the growing season originated about equally from mineral fertilizer N and N mineralized from soil organic matter. In comparison, nitrate was derived primarily from mineralization of soil organic matter (including microbially-modified fertilizer N) outside of the growing season. Nitrate derived from manure or septic systems constituted only a minor part of the total N flux to groundwater in the watershed. The relationship between $\delta^{15}N$ and $\delta^{18}O$ in groundwater samples indicated that denitrification is occurring to a limited extent and does not significantly deplete nitrate within the aquifer.

Similar to the isotopic results, simulations using LEACHN (Jiang et al. 2011) predicted occurrence of high drainage and soil nitrate concentration following potato harvest under a conventional barley-red clover-potato rotation system in the autumn winter-spring period in PEI (Fig. 13.4). Both the isotopic and modeling results highlighted that nitrate leaching from potato production occurred primarily outside of the growing season in PEI.

13.4 Management of Nitrate Leaching in Potato Production

Management strategies that minimize nitrate accumulation during time periods when the risk of drainage is high will reduce the risk of nitrate loss to the groundwater. An array of Beneficial Management Practices (BMPs) has been developed to help minimize nitrate leaching from crop production within different cropping systems. Choice of the rate, timing and formulation of fertilizer N application (Zebarth and Rosen 2007), planting deep-rooted cover crops (Delgado et al. 1999), development and preferential planting of crops and crop varieties that have higher nutrient-use efficiency (Bergstrom 1987; Randall et al. 1997; Tilman et al. 2002), crop rotations or intercropping (Tilman et al. 2002) and landscape management (Chow et al. 1999; Tilman et al. 2002) have all been identified as BMPs to reduce N losses. A review of field studies by Baker (2001) and Shrestha et al. (2010) concluded that the overall effects of the BMPs on reducing nitrate leaching are variable, ranging from no effect to a 30% reduction in nitrate leaching losses. Kraft and Stites (2003) noted that although most orthodox nitrate control strategies (e.g., decreasing and splitting fertilizer N applications, irrigation scheduling) have already been implemented in the irrigated potato production systems in the Wisconsin Central Sand Plain, nitrate loading to groundwater remained high. This reflects the challenges for controlling nitrate leaching from potato production systems over sensitive aquifers.

The key objective of the BMPs is to limit the accumulation or mobility of nitrate in the soil for the period when crop uptake is low or absent and drainage is occurring (Meisinger and Delgado 2002). The challenge is that almost all non-leguminous crops need N inputs as mineral or organic fertilizer, or require biological N fixation within the crop rotation, to achieve economic crop yields. This is particularly true for the potato crop where high fertilizer N rates are commonly required to achieve tuber size requirements (Zebarth and Rosen 2007). Furthermore, growers may apply additional N as “insurance N” to avoid the risk of yield loss (Mitsch et al. 1999). However, it is inevitable that some loss of N occurs from agricultural systems, and the risk of loss increases rapidly as N rate increases above the optimum (van Es et al. 2002).

In Eastern Canada, a number of BMPs have been evaluated to improve the fertilizer N management in the potato crop. These include choice of rate, timing and form of N applied (Chap. 10) and use of soil- and plant-based diagnostic tests to improve at-planting and in-season N management (Chap. 11). These BMPs were evaluated with respect to potato crop response (tuber yield and quality and plant N uptake) and residual soil nitrate, however no estimates of nitrate leaching were obtained.

Tile drainage experiments were performed to evaluate the ability of wheat straw mulch or an autumn seeded cover crop to reduce nitrate leaching following an early harvested potato crop (cultivar Superior) from spring 1989 to spring 1993 (Milburn and MacLeod 1991; Milburn et al. 1997). Application of a wheat straw mulch at a rate of 3000 kg ha^{-1} and lightly incorporated into the soil with a single pass of a disc harrow after early harvested potato reduced annual flow-weighted leached nitrate concentrations by 16% and 35% in the 1989–1990 and 1991–1992 leaching seasons, respectively, compared with conventional fallow practice (Milburn et al. 1997; MacLeod and Sanderson 2002). The reduction in nitrate leaching was attributed to net immobilization of soil nitrate by the high C/N ratio wheat straw. Autumn seeded winter wheat following early harvested potato was shown to reduce annual flow-weighted leached nitrate concentrations by 31% and 13% in the 1989–1990 and 1991–1992 leaching seasons, respectively, compared with conventional fallow practice (Milburn et al. 1997; MacLeod and Sanderson 2002). However, the use of cover crops or straw mulch may not always work efficiently. The growing season in eastern Canada is relatively short and the commonly-grown potato cultivar (Russet Burbank) is harvested late in the year. As a result there may not be sufficient time for N uptake by an autumn seeded cover crop, or for significant immobilization of N by a straw mulch, before the winter season in most years.

Tile drainage experiments and soil nitrate measurements were also performed to examine the effect of the timing of red clover plough-down on nitrate leaching from barley-red clover-potato rotation systems. When red clover was incorporated in early autumn nitrate concentration in tile-drain effluent was higher, and soil nitrate in the subsequent spring was lower, than when incorporation was delayed until late autumn or spring (Sanderson et al. 1999; Sanderson and MacLeod 2002). When the rate of N fertilizer application to the potato crop was not reduced to account for the additional N retained following late incorporation of the red clover crop, the additional N resulted in increased nitrate leaching following the subsequent potato harvest.

Mean flow-weighted nitrate concentrations of tile drainage over the autumn winter and spring following potato harvest from 1989 to 1992 under a barley-potato rotation were consistently above 10 mg NO_3-N L^{-1} (average 17 mg NO_3-N L^{-1}) except the concentration (8.8 mg NO_3-N L^{-1}) from the treatment of winter wheat in 1989 (Milburn et al. 1997). This was the case regardless of wheat straw mulch or autumn seeded cover crop treatments. In comparison, flow-weighted nitrate concentrations in tile drainage following barley in the potato-barley rotation systems averaged 5.5–6.5 mg NO_3-N L^{-1}. Mean flow-weighted nitrate concentrations of tile drainage over the autumn winter and spring following potato harvest from 1993 to 2004 under a conventional barley-red clover-potato rotation were consistently above 10 mg NO_3-N L^{-1} (average 19.2 mg NO_3-N $L^{-1)}$ while the nitrate concentrations in tile drainage following barley and red clover averaged 7.1 and 8.2 mg NO_3-N L^{-1}, respectively (MacLeod, unpublished data). In contrast, nitrate concentrations from wells in forested areas, where natural background concentrations of nitrate are present, were typically less than 2 mg NO_3-N L^{-1} (Jiang and Somers 2009). These findings suggest that potato productions systems have the potential to result in nitrate loading well above background concentrations, and that the risk of nitrate leaching is primarily associated with the potato phase of conventional barley-red clover-potato rotations.

Nitrate leaching from conventional potato production systems was also simulated using LEACHN (Jiang et al. 2011). Model inputs related to soil, climate and managements were derived from measurements at the above tile drainage facility. The model was calibrated and verified against measured nitrate concentrations of tile drainage and water levels for the period 1999–2008 through coupled LEACHN and MODFLOW simulations. Simulations were conducted for multiple cycles of barley-potato (2-year) and barley-red clover-potato (3-year) given recommended fertilizer N rates for potato, barley and red clover as 200, 60 and 0 kg N ha^{-1}, respectively, over the period of 1999 and 2008. Simulations using fertilizer N rates of 0, 50, 100, 150 and 200 kg N ha^{-1} for the potato crop, holding N management for the barley and red clover crops constant, were also performed.

Annual nitrate leaching and leached nitrate concentration were predicted to increase with increasing fertilizer N rate for potato crop, and to be greater from

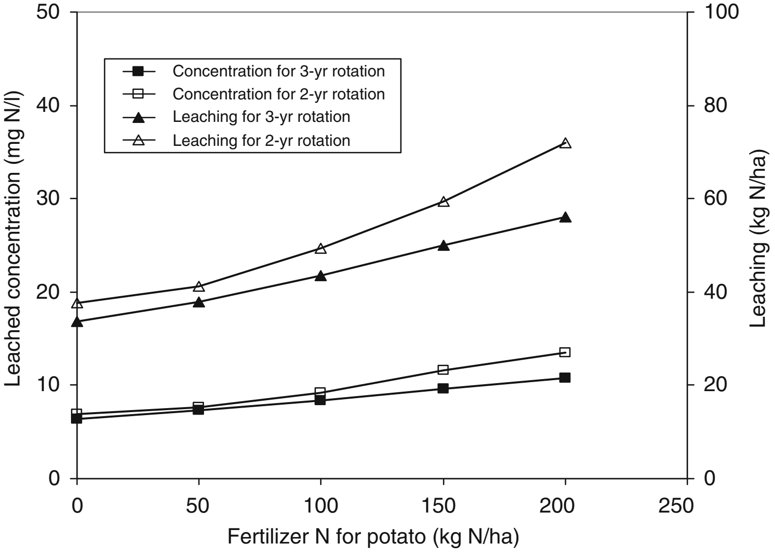

Fig. 13.5 Long-term average annual nitrate leaching from barley-red clover-potato (3-year) and barley-potato rotation (2-year) production systems as affected by fertilizer N for potato crop, simulated using LEACHN. Fertilizer N rate for barley and red clover were held constant at 60 and 0 kg N ha^{-1}, respectively

the 2-year potato rotation compared with the 3-year potato rotation (Fig. 13.5). For current typical fertilizer N application rates (150–200 kg N ha^{-1}), annual average nitrate leaching for 2-year and 3-year rotation systems were predicted to be 60–72 and 50–56 kg N ha^{-1}, respectively, and the corresponding leached concentrations were predicted to be 11.6–13.5 and 9.6–10.7 mg NO_3-N L^{-1}, respectively. Even when the fertilizer N rate for potato was reduced to 0 kg N ha^{-1}, the model predicted annual average nitrate leaching of 38 and 34 kg N ha^{-1} (leached nitrate concentrations of 6.9 and 6.4 mg NO_3-N L^{-1}) for 2- and 3-year rotation systems respectively. This suggests that significant nitrate leaching can occur from potato production systems even under low fertilizer N input for potato crops but recommended N application for barley, at least over limited time periods. When the potato crop received fertilizer N application rates of 150–200 kg N ha^{-1}, approximately 50–60% of the nitrate leaching losses were associated with the barley and red clover phases of the rotation. This suggests there is the potential to reduce nitrate leaching not just under potato production, but also under potato rotation crops.

Nitrate leaching from the representative 3-year rotation system barley-red clover-potato was simulated using LEACHN (Fig. 13.6). Annual nitrate leaching was predicted to range from 27–91 kg N ha^{-1} with an average of 56 kg N ha^{-1}, depending on crop species, management practices and climatic conditions. Plant N uptake and N harvest index for each crop were assumed to be constant over the simulation period, and therefore the annual variation of nitrate leaching primarily reflected the effects of variation in climatic conditions. Nitrate leaching was generally higher

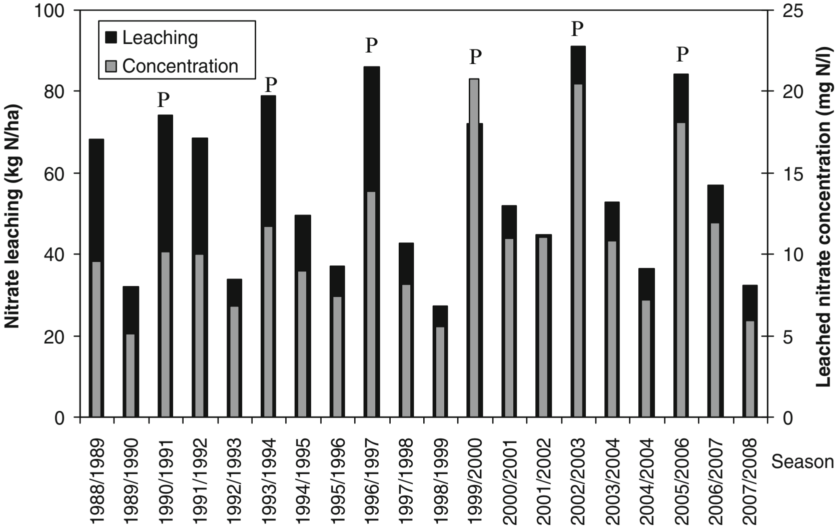

Fig. 13.6 Annual nitrate leaching for the October to April period from a conventional barley-red clover-potato rotation in PEI simulated using LEACHN. All the input parameters except weather were held constant for each cycle of the rotation(The bars marked with "P" represent overall nitrate leaching and flow-weighted leached nitrate concentration during the period after potato harvest and before planting barley crop)

following a potato crop (72–91 kg N ha^{-1}, average 81 kg N ha^{-1}) compared with the rotation crops of barley (43–69 kg N ha^{-1}, average 56 kg N ha^{-1}) or red clover (32–45 kg N ha^{-1}, average 35 kg N ha^{-1}). The model predicted that nitrate leaching outside of the growing season accounted for between 72% and 98% of the annual leaching, with an average of 86%. The predicted magnitude and timing of nitrate leaching generally agreed with the isotopic evidence discussed above and those reported by Delgado et al. (2001a), De Neve et al. (2003), Peralta and Stockle (2001) and Vos and van der Putten (2004). In comparison, predicted N leaching as NH_4^+ ranged from 0–0.8 kg N ha^{-1} with an average of 0.4 kg N ha^{-1}. Annual N losses through denitrification were predicted to vary from 0.2–8.3 kg N ha^{-1} with an average of 2.4 kg N ha^{-1}, and fell in the ranges of values reported by Hoffmann and Johnsson (2000) and Zebarth and Rosen (2007). As expected, N losses through NH_4^+ leaching and by denitrification were predicted to be much less significant than nitrate leaching.

These findings suggest that three general approaches may be most effective in reducing nitrate leaching losses from potato production systems in PEI. First, nitrate leaching occurs primarily from the potato phase of potato rotations. Consequently, increasing the length of potato rotations, for example from current 3-year to 4-year rotations, and reducing the proportion of land in potato production within a watershed, should reduce the overall nitrate loading within a given watershed. Second, N management practices and BMPs that reduce the risk of nitrate accumulation in soil during the potato rotation, especially residual nitrate at potato harvest, may reduce the risk of nitrate leaching. These practices may include improved crediting of soil N mineralization from soil organic matter and crop residues, use of in-season measures of crop N status to guide in-season N management, and introducing potato cultivars with lower fertilizer N requirements or higher N use efficiency. Third, N management practices and BMPs that reduce the availability of nitrate for leaching during the rotation crop phases. This could include delayed plough-down of forage crops until spring, or until late autumn when soil temperatures are reduced and the rate decomposition is reduced. It could also include introduction of alternative rotation crops, and implementing N management practices for the rotation crops.

13.5 Conclusions

Nitrate leaching from agricultural production systems is of economic importance, and is also of concern both for drinking water quality and the health of aquatic ecosystems. Nitrate leaching occurs when moving water and nitrate coexist in soil. Intensive agricultural crop production systems with high N inputs in coarse-textured soil and under humid climatic conditions present a high risk of nitrate leaching. Elevated nitrate nitrogen in groundwater and associated surface water in PEI was attributed to the configuration of intensive potato cropping in sandy soil over a shallow unconfined and semi-confined sandstone aquifer under a humid climate. Nitrate leaching from conventional barley-red clover-potato rotation systems primarily occurred during autumn winter and spring when crop uptake diminishes, and nitrate from mineralization and fertilizer residual and excessive moisture from rainfall and snowmelt infiltration coexists in the soil in PEI. This finding was supported by tile drainage experiments, isotopic evidences, long-term hydrological monitoring and LEACHN simulations. The LEACHN model predicted that about 50–60% of the nitrate leaching losses were associated with the barley and red clover phases, suggesting there is the potential to reduce nitrate leaching not just in the potato phase, but also in the rotation crop phases. The requirement for high N inputs to obtain economic tuber yields, in combination with the high risk of nitrate loss from the root zone, present significant challenges to growers with respect to N management. Reducing the frequency of potato in the crop rotation, and use of practices to reduce residual nitrate in potato phase as well as the rotation crop phases, will be most effective in reducing nitrate leaching losses.

Future studies should investigate the opportunities of minimizing nitrate accumulation in the soil both during and outside of the growing season both in the potato phase and the rotation crop phases. Development of improved practices with respect to the selection of rate, timing and form of fertilizer N products (Chap. 10) and development of soil- and plant-based diagnostic tests to guide at-planting and in-season fertilizer N management (Chap. 11) will be important in reducing the risk of nitrate leaching. Development of potato cultivars with low N input requirements and high N use efficiency may also reduce the risk of nitrate leaching (Zebarth and Rosen 2007). The effects of BMPs developed to minimize nitrate leaching losses from potato production systems outside of the growing season, such as incorporation of wheat straw, planting cover crops following potato crops, and delayed red clover plough-down, have been tested with various degrees of success in PEI. The potential effects of these BMPs on reducing nitrate leaching losses should be evaluated through well-designed field tests and modeling at field and watershed scales in eastern Canada. In addition, the possibilities of growing other high value and low N input crops and removing legume crops, such as red clover, out of potato rotation systems should be explored.

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