Review: Reducing residual soil nitrogen losses from agroecosystems for surface water protection in Quebec and Ontario, Canada: Best management practices, policies and perspectives

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[1]Department of Natural Resource Sciences, Macdonald Campus, McGill University, 21,111 Lakeshore Road, Ste-Anne-de-Bellevue, Quebec, Canada H9X 3V9; [2]Department of Bioresource Engineering and Brace Centre for Water Resources Management, Macdonald Campus, McGill University, 21,111 Lakeshore Road, Ste-Anne-de-Bellevue, Quebec, Canada H9X 3V9.

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Rasouli, S., Whalen, J. K. and Madramootoo, C. A. 2014. **Review: Reducing residual soil nitrogen losses from agroecosystems for surface water protection in Quebec and Ontario, Canada: Best management practices, policies and perspectives**. Can. J. Soil Sci. **94**: 109–127. Eutrophication and cyanobacteria blooms, a growing problem in many of Quebec and Ontario's lakes and rivers, are largely attributed to the phosphorus (P) and nitrogen (N) emanating from intensively cropped agricultural fields. In fact, 49% of N loading in surface waters comes from runoff and leaching from fertilized soils and livestock operations. The residual soil nitrogen (RSN), which remains in soil at the end of the growing season, contains soluble and particulate forms of N that are prone to being transported from agricultural fields to waterways. Policies and best management practices (BMPs) to regulate manure storage and restrict fertilizer and manure spreading can help in reducing N losses from agroecosystems. However, reduction of RSN also requires an understanding of the complex interactions between climate, soil type, topography, hydrology and cropping systems. Reducing N losses from agroecosystems can be achieved through careful accounting for all N inputs (e.g., N credits for legumes and manure inputs) in nutrient management plans, including those applied in previous years, as well as the strategic implementation of multiple BMPs and calibrated soil N testing for crops with high N requirements. We conclude that increasing farmer awareness and motivation to implement BMPs will be important in reducing RSN. Programs to promote communication between farmers and researchers, crop advisors and provincial ministries of agriculture and the environment are recommended.

Key words: Non-point source pollution, eutrophication, agricultural policy

Rasouli, S., Whalen, J. K. et Madramootoo, C. A. 2014. **La réduction des pertes d'azote résiduel du sol dans les écosystèmes agricoles en vue de la protection des eaux de surface au Québec et en Ontario (Canada): pratiques exemplaires, politiques et perspectives**. Can. J. Soil Sci. **94**: 109–127. On attribue dans une large mesure l'eutrophisation et la prolifération des cyanobactéries, problème grandissant dans de nombreux lacs et cours d'eau du Québec et de l'Ontario, au phosphore (P) et à l'azote (N) qui émanent des champs cultivés intensivement. À dire vrai, on doit 49% du N qui échoue dans les eaux superficielles au ruissellement et à la lixiviation sur les sols fertilisés ainsi qu'à l'élevage des animaux domestiques. L'azote résiduel du sol (ARS), c'est-à-dire qui demeure dans le sol à la fin de la période végétative, se compose de N soluble et de particules susceptibles d'être transportés des champs aux cours d'eau. Les politiques et les pratiques exemplaires visant à réglementer le stockage du fumier et à restreindre l'épandage de celui-ci et des engrais peuvent concourir à réduire les pertes de N dans les écosystèmes agricoles. Toutefois, diminuer la quantité d'ARS exige aussi qu'on saisisse bien les interactions complexes entre le climat, la nature du sol, la topographie, l'hydrologie et les systèmes culturaux. On pourrait réduire la quantité de N perdue par les écosystèmes agricoles en comptabilisant minutieusement tous les apports de N (à savoir, le N venant des légumineuses et du fumier) dans les plans de gestion des éléments nutritifs, y compris les apports des années antérieures, ainsi qu'en appliquant de manière stratégique de multiples pratiques exemplaires et un dosage du sol adapté aux cultures très avides d'azote. En conclusion, les auteurs croient que des agriculteurs plus sensibilisés et plus enclins à adopter des pratiques exemplaires auront leur importance pour la réduction de l'ARS. On préconise des programmes qui faciliteront les échanges entre producteurs et chercheurs, agronomes et ministères provinciaux de l'Agriculture et de l'environnement.

Mots clés: Pollution par des sources non ponctuelles, eutrophisation, politiques agricoles

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Abbreviations: **AEAC**, agri-environmental advisory clubs; **BMP**, best management practice; **CD**, controlled drainage; **DON**, dissolved organic nitrogen; **EFP**, Environmental Farm Plan; **NMS**, nutrient management strategy; **NMP**, nutrient management plan; **PAA**, Agri-Environmental Support Program; **PAEF**, agroenvironmental farm plan; **PET**, potential evapotranspiration; **PON**, particulate organic nitrogen; **RSN**, residual soil nitrogen; **SI**, subirrigation; **SOM**, soil organic matter

Many lakes and rivers in Quebec and Ontario have become increasingly eutrophic, experiencing episodic blooms of algae and impaired water quality. Eutrophication and cyanobacterial outbreaks have been reported nearly every summer since 1999 in Missisquoi Bay of Lake Champlain in southern Quebec [Corporation Bassin Versant Baie Missisquoi (CBVBM) 2003], since 1988 in the Yamaska River Basin in southwestern Quebec, and since the 1970s in Lake Erie, Lake Superior and Lake Simcoe in southern Ontario (Chambers et al. 2001; Lake Simcoe Environmental Management Strategy 2003).

Phosphorus (P) is considered to be the critical limiting nutrient for eutrophication of freshwater systems, but a combination of P and nitrogen (N) can be limiting for algae in a variety of freshwater systems, including lakes, reservoirs, and streams (Schindler 1974; Smith et al. 1999; Howarth and Marino 2006). According to Chambers et al. (2012), levels of total N exceeding 1.1 mg L^{-1} in Quebec and Ontario streams contribute to eutrophication and impairment of water quality. Elevated levels of N may also contribute to groundwater contamination and surface water acidification (Rabalais 2002). Nitrate levels greater than 45 mg L^{-1} (equivalent to 10 mg L^{-1} nitrate-nitrogen) in groundwater can cause methaemoglobinemia, long considered to pose a health risk to humans exposed to nitrate in drinking water (Food and Agriculture Organisation of the United Nations/World Health Organization 2003). In this paper, we will be focusing on the direct impact of nitrate on surface waters.

Nitrogen enrichment in Canadian surface waters is largely attributed to the agricultural sector, which is responsible for 49% of N loading to surface water, mostly through runoff and leaching from fertilized soils and livestock operations (Chambers et al. 2001; Janzen et al. 2003). Gaseous forms of N, such as ammonia and nitrous oxides originating from agricultural activities, also enter surface waters through wet and dry deposition. As a result, 80% of the total N load in surface water is attributable to agriculture (Chambers et al. 2001). Based on the Statistics Canada 2006 census data (Statistic Canada 2007), the average N inputs from atmospheric deposition, synthetic fertilizers, manure, biological N_2 fixation and crop residue, totaled 133.2 kg N ha^{-1} in Quebec farmlands and 137 kg N ha^{-1} for Ontario (De Jong et al. 2009). On average, only 59% of N inputs are recovered in crop biomass (Liu et al. 2010), leaving more than 40% of N that may remain as residual soil N (RSN). The RSN, which is mineral N remaining in soil at the end of growing season (Drury et al. 2007), ranged from 20 to 30 kg N ha^{-1} in Quebec farmlands and 30 to 50 kg N ha^{-1} in Ontario farmlands during the period 1981 to 2006 (De Jong et al. 2009). If soils receive surplus water (e.g., from rainfall, snowmelt), RSN may be transmitted to surface waters through leaching, tile drainage and/or surface run-off. Approximately 2 million ha of croplands in these provinces are subsurface tile drained (Helwig et al. 2002), particularly in the southern portion of Quebec and Ontario where corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] are produced. About 35 to 49% of annual rainfall in this region discharges as tile drainage water (Simard 2005).

Soluble N compounds in the RSN pool, particularly nitrate (NO_3-N), are readily leached from agricultural fields. The amount of NO_3-N lost from fields in drainage water ranged from 7.2 to 11.7 kg N ha^{-1} in Quebec's farmlands and 8.4 to 9.4 kg N ha^{-1} in Ontario farmlands from 1981 to 2006 (De Jong et al. 2009). In a 3-yr study in southwestern Ontario involving corn–oat (*Avena sativa*)–alfalfa (*Medicago sativa*) rotations and conventional tillage practices, NO_3-N concentrations in tile drainage water averaged 16.5 mg L^{-1} (Tan et al. 2002b), exceeding the water quality limit for eutrophication and harmful algal blooms (1.1 mg N L^{-1}; Chambers et al. 2012). Other soluble N forms such as dissolved organic N (DON) are also found in leachate and runoff from intensive livestock operations (Anderson and Cabana 2005). Van Kessel et al. (2009) reported DON concentrations between 0.2 and 3.5 mg N L^{-1} in leachate from agricultural soils, with higher DON concentrations associated with manure-amended soils. Therefore, agricultural soils with a history of manure application, such as those near dairy farms and confined livestock production facilities (e.g., poultry and swine) could also be a source of DON entering waterways in Quebec and Ontario (Schindler 2006). In addition, microbial breakdown of organic compounds such as proteins releases amino acids that could enter the DON pool. Soils receiving N-rich organic residues like soybeans are therefore expected to have higher DON concentrations than those receiving inorganic N fertilizer only (Neff et al. 2000; Shand et al. 2000; Kalbitz and Geyer 2002). Also, inorganic N inputs may affect the release of DON as mineral N fertilizer increases the microbial mobilization of amino acids followed by a condensation of carbohydrates to humic substances (Kalbitz and Geyer 2002).

Particulate N, including exchangeable NH_4-N and organic N bound to clay particles and erodible organo-mineral fractions, is another component of the RSN pool. Concentrated in the topsoil (plow layer), particulate N is susceptible to loss through surface runoff or being transported through the soil macropore network leaving the fields through tile drains (Simard 2005). Cade-Menun et al. (2013) reported that 9 to 20% of total N concentration that is transported in surface runoff from Saskatchewan croplands is in the form of particulate organic N (PON). A study conducted in western Canada by Tiessen et al. (2010) reported the contribution of PON to annual TN losses in surface runoff from a clay loam soil was 12% and 26% under conventional and conservation tillage, respectively. According to

Carter et al. (2003), the PON fraction accounted for up to 27% of the total N loss in tile drain outflow in agricultural experimental sites in eastern Canada. Globally, organic N associated with sediments (PON) exported from agricultural catchments to rivers is between 0.02 and 29.7 kg N ha^{-1} yr^{-1} (Alvarez-Cobelas et al. 2008). However, there is little information on the quantities of PON lost from agricultural soils in Quebec and Ontario.

Given that the RSN pool contains soluble and particulate forms of N that are at risk of being transported from agricultural fields, can we use information about RSN to reduce N loading to surface waters in Quebec and Ontario? Many best management practices (BMPs) aim to control N pollution in waterways by maximizing N use-efficiency (or yield) and reducing RSN. There is a sense that policies regulating manure storage and restricting fertilizer and manure spreading periods will also limit the RSN. However, despite the promotion of these BMPs and policies, many agricultural soils in Quebec and Ontario still have high RSN (De Jong et al. 2009). This is attributed to the complex interactions between climate, soil type, topography, hydrology and cropping systems, all of which affect the RSN pool and consequently N losses from agricultural lands in the region (St. Luce et al. 2011).

Our objective is to review the factors that influence the RSN pool in relation to soluble and particulate N losses from Quebec and Ontario agroecosystems. This information will be used to assess the effectiveness of BMPs and other policies, including regulations, to reduce soluble and particulate N loading of surface waters. The first section of the review deals with N dynamics relevant to understanding RSN transformations. The second section presents a comprehensive review of the physical and agricultural management controls on the amount and forms of RSN, and relates this to soluble and particulate N exports. The third section focuses on BMPs and policies in Quebec and Ontario that attempt to minimize RSN, and consequently N losses from agroecosystems. We conclude with perspectives on the potential of various interventions to reduce N losses from agroecosystems.

NITROGEN DYNAMICS IN AGROECOSYSTEMS: RELEVANCE TO RESIDUAL SOIL NITROGEN

Plant-available N (NH_4-N and NO_3-N, also referred to as mineral N) is added to agroecosystems by fertilizer and manure applications, atmospheric deposition, and also comes from mineralization of soil organic N and crop residues. Fertilizer and manure are typically applied at agronomic rates to meet crop N requirements, which can be up to 200 kg N ha^{-1} for N-demanding crops such as corn, cabbage and tomatoes. Wet and dry N depositions add mineral N; in eastern Canada, annual wet N deposition is less than 5 kg NO_3-N ha^{-1} ($<$1.2 kg N ha^{-1}), while southern Ontario receives the highest levels of atmospheric N deposition in Canada, up to 15 kg NO_3-N ha^{-1} yr^{-1} (3.5 kg N ha^{-1}) (Vet and Shaw 2004). The soil organic N pool contains 2000 to 6000 kg N ha^{-1} depending on soil organic matter content, organic inputs, soil depth, and soil physical characteristics. Of this, about 1 to 2.5% may be mineralized each year [Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ) 2010]. Mineralization rates are generally higher in sandy soils than clayey soils due to better aeration and less physical protection of organic matter, and in warmer regions than cooler regions (Griffin 2008; Sahrawat 2008). However, the relatively lower organic matter content in sandy soils may result in lower N in leachate compared to clayey soils. Decomposition of crop residues and organic N compounds in manure release NH_4-N, with greater release expected from young green manure, leguminous crop residues, and liquid and semi-solid manure (CRAAQ 2010).

Mineral N is available to plants, but not all the mineral N added or generated from microbially mediated mineralization in soil is used by plants. The RSN pool is subject to chemical and biological transformations that lead to gaseous N losses (NH_3, N_2O, N_2) or assimilation by microorganisms. Following immobilization in the microbial biomass, the N can be released as DON, NH_4-N and NO_3-N or it may persist as organic N associated with soil minerals. Mineralization of organic N occurs during the growing season and most N remaining from the previous growing season is lost from the soil profile by leaching and/or denitrification due to high soil moisture (Zebarth et al. 2009). In some soils of eastern Canada, up to 34% of recently added NH_4-N is fixed by soil clay minerals (Chantigny et al. 2004). Dissolved N compounds (DON, NH_4-N and NO_3-N) are components of soluble N that are present in leachates and runoff water, while N in organo-mineral complexes and fixed NH_4-N are included in the pool of particulate N in drainage water and runoff from agricultural fields.

Accumulation of RSN in agricultural soils and its transport from soil to water bodies is influenced by factors such as precipitation, soil texture, hydrological pathways, N inputs, crop type and rotation, tillage and land drainage. The next section deals with the impact of these factors on RSN accumulation and movement from the root zone to surface waters.

CLIMATIC, HYDROLOGICAL AND AGRICULTURAL PRACTICE CONTROLS ON RESIDUAL SOIL NITROGEN LOSSES FROM AGROEOSYSTEMS

Climate Effect

Transport of soluble forms of RSN to surface waters occurs as a function of the volume of water flowing over the soil surface or passing through the root zone. The amount of water leaving the soil depends on precipitation and soil properties (e.g., texture, infiltration rate, etc.). Average annual precipitation is 900 to 1200 mm in Quebec and 750 to 1200 mm in Ontario. According to De Jong et al. (2009), the 6-yr mean overwinter precipitation (2001 to 2006) was 558 mm in Quebec and 513 mm in Ontario, which create an average drainage of 202 mm in Quebec and 186 mm in Ontario and an average surface runoff of 200 mm in both provinces. Loss of RSN in drainage water was up to 68 kg N ha^{-1} for Quebec and 47 kg N ha^{-1} for Ontario farmlands during the non-growing season. Growing season N losses in Quebec and Ontario were approximately 24 and 19% of those occurring during the non-growing season. In these agroecosystems, the largest portion of N lost to surface waters occurs via soil drainage. Intensity of rainfall also influences the erosion of N-rich particles that leave agricultural fields either by preferential flow or in surface runoff. More erosion occurs when soil moisture is high and evapotranspiration is low (Randall and Mulla 2001), which corresponds to field conditions in Quebec and Ontario during the frost-free period when crops are not growing (e.g., early spring, late fall).

Most of the RSN remaining from the previous growing season is lost through percolation from the crop root zone during the non-growing season, due to high soil moisture (Zebarth et al. 2005, 2009). For example, De Jong et al. (2009) estimated losses of up to 14.7 and 22.9 kg N ha^{-1} from November to May in Ontario and Quebec, respectively. In these provinces, the deeper soil horizons are warmer than the topsoil during the winter months due to the geothermal gradient. This allows nitrification to continue in the soil profile over winter (Miller et al. 2007). The NO_3-N produced from this process is expected to percolate through the soil profile and may be lost in tile drain outflows during snowmelt and heavy rainfall events in early spring.

Build-up of RSN may occur during a dry summer due to the mineralization of SOM, the absence of leaching and reduced N uptake by plants (Stanhope et al. 2009). With rewetting rainfall, greater NO_3-N leaching can be expected due to higher concentrations of soil mineral N and higher drainage water flow (Randall and Mulla 2001). Jaynes et al. (1999) reported N losses in association with summer tile drain discharges, specifically when fertilizers (chemical or manure) were applied in the early summer. Wetting and drying cycles also cause soil macroaggregates to break apart, exposing physically protected organic matter to erosion, degradation and mineralization (Lundquist et al. 1999).

Air temperature, which directly affects potential evaporation and transpiration and consequently all components of the soil–water balance, is expected to have little effect on N leaching, especially in the non-growing season. De Jong et al. (2007) projected a decrease in RSN losses of only 1.4% when daily maximum and minimum air temperatures were increased by 15%. This was due to higher drainage volumes in the non-growing season, regardless of temperature. Temperature affects the biological processes that control mineralization, nitrification and immobilization. Warmer temperatures are expected to increase the amount of NO_3-N in soil solution, which is susceptible to leaching as water drains through the soil profile. However, some studies reported less soluble N loading of surface waters during summer months than other times of the year due to an increase in N uptake by vegetation, as well as denitrification in soil, streams and near-stream zones (e.g., Geyer et al. 1992; Cirmo and McDonnell 1997).

Hydrologic Processes

Both surface and subsurface hydrological pathways are important for transporting soluble and particulate N from the RSN pool (Iqbal and Krothe 1995; Peterson et al. 2002; Petry et al. 2002; Silva et al. 2005). Incoming rainfall, melting snow and irrigation water either percolate through the soil profile by matrix and preferential flow, or exceed the soil infiltration capacity and run off the soil surface. Soil texture and topography exert a major control on these hydrological pathways for transporting N from agricultural soils. These factors can be modified by installations such as tile drains, surface inlets and buffer strips, which alter hydrologic patterns. We outline the basic hydrological processes controlling RSN transport from agroecosystems in this section, and will discuss how agricultural management can alter partitioning of water amongst flow pathways in the next section.

Surface Runoff

Surface runoff can be a significant pathway for N loss on undulating agricultural land and on poorly drained clayey soils (Oenema and Roest 1998). Silt loams, very fine sandy loams and loams are also at the risk of generating surface runoff when they become waterlogged and experience ponding at the soil surface. Surface runoff can be generated by rainfall, snowmelt or irrigation. Topography determines both the convergence and velocity of water flow, with steeper slopes increasing the risk of soluble and particulate N loss in concert with soil erosion (Hairsine and Rose 1992). D'Arcy and Carignan (1997) showed that nearly half of the variability in soluble N concentration was related to catchment slope in the Canadian Shield of southern Quebec, with higher N concentrations in surface runoff from rolling regions. When the regional surface gradient is relatively flat, the routing of runoff is mainly determined by microtopography, which influences the retention of water that does not flow, but is held in depressions to await infiltration or evaporation (Antoine et al. 2009).

Runoff is generated from three dominant processes: (i) Hortonian overland flow due to infiltration excess, (ii) saturation overland flow due to saturation excess, (iii) lateral subsurface flow in the soil (Naef et al. 2002). Given the distribution of precipitation and weather patterns in Quebec and Ontario, saturation excess runoff is the most common runoff mechanism in this region. Overland flow is the result of cumulative rainfall and snowmelt events rather than isolated, intensive rainfall events (Lapp 1996). Under these climatic conditions, saturation excess runoff from a particular field is largely a function of landscape position, water table height, stream levels, impermeable subsoils, slope breaks and convergent subsurface flows.

High intensity rainfalls increase both surface runoff and the loss of particulate N with eroded topsoil (Smith et al. 2001). In spring and fall, when the soil profile is saturated with water from repeated rainfall events and evapotranspiration rates from bare soil are low, the risk of N loss by surface runoff in soluble and particulate forms is higher. Surface runoff can cause significant PON loss (e.g., up to 65% of total N; Sharpley et al. 1987). Cade-Menun et al. (2013) reported PON concentration ranging from 0.2 to 0.7 mg L^{-1} in snowmelt runoff of from fertilized annual cropland in Saskatchewan. Drury et al. (2009) found that flow weighed NO_3-N concentrations in surface runoff from a fertilized clay loam soil varied from 0.43 to 3.87 mg N L^{-1}. In an Albertan field study, NO_3-N loading ranged from 0.04 to 13.2 mg N L^{-1} in cultivated non-manured sites, and from 0.41 to 43.4 mg N L^{-1} in manured sites during spring surface runoff (Casson et al. 2008). Jiao et al. (2012) reported that NO_3-N losses in surface runoff accounted for 58% of TN losses in a 3-yr experimental period.

Although it is a challenge to determine what proportion of RSN may be lost through surface runoff due to the extreme non-linearity and watershed dependence of this transport pathway (Sarle 1994), more N loss is expected during spring and fall rainfall events and from poorly drained soils.

Subsurface Flow

Much of the land in Quebec (95%) and Ontario (70%) lies on the Canadian Shield and is composed of glacial deposits of boulders, gravel and sand. Postglacial seawater and lakes have left thick clay deposits on some parts of the Shield (Card 1990). Consequently, soils located on rolling hills have a predominantly coarse texture (e.g., loamy with coarse fragments or sandy/loamy) overlying a clayey/loamy subsoil layer. Agricultural activities in Quebec occur mostly in the St. Lawrence Lowlands, a relatively flat region with clayey soils or coarse-textured soils overlying clay deposits left behind by the Champlain Sea. Agricultural land in southern Ontario is located in the Great Lakes–St. Lawrence Lowlands, which is dominated by clayey soils. Therefore, the existence of the naturally poor drainage conditions in clayey subsoil impedes water drainage and generates subsurface lateral movement of water.

The generation of subsurface flow depends on rainfall or irrigation events, and soil properties such as hydraulic conductivity and texture (Naef et al. 2002; Chae et al. 2004; Silva et al. 2005). The subsurface flow pathway is important in well-drained sandy soils with imperfect external drainage, imperfectly drained loamy and clayey soils and in soils with shallow water tables and/or tile drain systems (Oenema and Roest 1998). Subsurface water movement can occur through the soil matrix and/or by preferential flow (by-pass flow). Slower percolation of water through the soil matrix is expected, whereas preferential flow is the more rapid and direct transfer of surface water through preferred pathways like macropores (Reid et al. 2012). Soil macropores include root channels, earthworm burrows, large pores, cracks or others semi-continuous voids within the soil, which act as a rapid by-pass from upper to lower soil horizons.

Soil texture influences hydraulic properties (water retention, infiltration, porosity) that govern the flow pathway (matrix vs. preferential) for water and nutrients, including RSN, through the soil profile. In clayey soils, preferential flow pathways are responsible for transporting up to 90% of water and N through the soil profile and into the tile drains (Li and Ghodrati 1997; Simard et al. 2000). While preferential flow can also occur in coarse-textured soils (Kung et al. 2000), N is more easily leached through the porous matrix of these soils (Dosskey and Bertsch 1994; McClain et al. 1997; Campbell et al. 2000). In agricultural soils of Quebec and Ontario, this could result in subsurface outflow from the lowest coarse-textured soil layer, or water could continue to move down through the marine clay subsoil, probably by preferential flow, before exiting the field through tile drains. A feature of agricultural soils in southern Quebec and southwestern Ontario is that swell–shrink clay minerals in the soil profile tend to form cracks during the summer months that can act as preferential flow pathways for transporting RSN during rainfall events. When fields are tile drained and macropores are connected to the drain lines, preferential flow becomes an important conduit for nutrient transport from soil to surface water (Grant et al. 1996). Many researchers have demonstrated that the subsurface flow pathway is the dominant pathway for NO_3-N transport (e.g., Baker 1980; Gilliam and Skaggs 1986; Skaggs et al. 1994). Pionke et al. (1999) showed significantly higher NO_3-N loads (70–90% of total N) in subsurface flow than in surface runoff in an agricultural watershed with silt loam soil located in the Chesapeake Bay Basin. In addition, suspended soil particles transported by overland flow (Heathwaite 1997), can be intercepted by surface macropores and transported through the soil profile to tile drains (Simard et al. 2000). Consequently, eroded soil particles that are typically enriched with organic matter and absorbed or occluded nutrients, can be transported to tile drains by preferential flow. Carter et al. (2003) reported that particulate-associated N represented up to 27% of the total N transported in tile drain outflow. Therefore, preferential flow pathways increase N loss by facilitating water movement through the soil profile.

Agricultural Practices

Agricultural practices affect the accumulation of RSN in the field and the transport of N from the soil profile.

The source and amount of N fertilizer inputs, timing of fertilizer applications, the choice of crops grown and tillage practices all influence the biological processes of the soil N cycle that affect the size and chemical composition of the RSN pool (Fig. 1). Soil water movement is influenced to some degree by crop type and rooting system (e.g., root channels act as macropores) and tillage (e.g., surface cover by residues, type of tillage), but even more by the installation of structures that artificially control water movement and outflows from the field (e.g., tile drainage, surface inlets, grassed waterways and vegetated buffer strips along the edge of fields). Thus, agricultural practices exert an important control on the transport of soluble and particulate components of RSN. These processes are described in the next sections. Since field crops in Quebec and Ontario are not generally irrigated, we do not consider the effect of irrigation on N loss from agroecosystems, although it could be important for vegetable crops. According to Statistics Canada (2011), the irrigated area in Quebec is 3% and in Ontario is 4% of total irrigated lands in Canada.

Tillage Practices

Tillage practices influence soil physical and biological properties that are important for hydrological processes and soil N transformations (Patni et al. 1998; Tan et al. 2002a). These can alter the size and composition of the RSN pool. Conservation tillage encompasses a group of practices that leave crop residues on the soil surface. Crop residues cushion the erosive impact of rain drops on the soil surface and slow surface flow, thus enhancing infiltration and reducing sediment transport with surface runoff (Kenimer et al. 1987). Conservation tillage practices tend to minimally disturb soil structure and macroporosity, which facilitates N and water movement through the soil profile (Follett and Delgado 2002). In contrast, tillage reduces water infiltration through the soil profile by disturbing the connectivity of macropores and rearranging the soil matrix. Consequently, tillage increases the susceptibility of surface soil to erosion and the generation of erodible sediments (Fawcett et al. 1994).

Some studies have reported greater RSN leaching in no-till systems compared with tilled systems (Patni et al. 1998; Tan et al. 2002b) due to formation of continuous soil macropores that increase NO_3-N movement through preferential flow. Conversely, others have reported greater NO_3-N leaching in tilled soils, partly due to higher rates of denitrification in no-till soils (Mkhabela et al. 2008), greater infiltration in tilled soils, or enhanced N mineralization in tilled soils (Constantin et al. 2010). Other authors have reported no effect of tillage on soluble N loss from soils (Stoddard et al. 2005; Fuller et al. 2010). St. Luce et al. (2011) concluded that the effect of tillage on NO_3-N leaching differs from year to year and between spatial units.

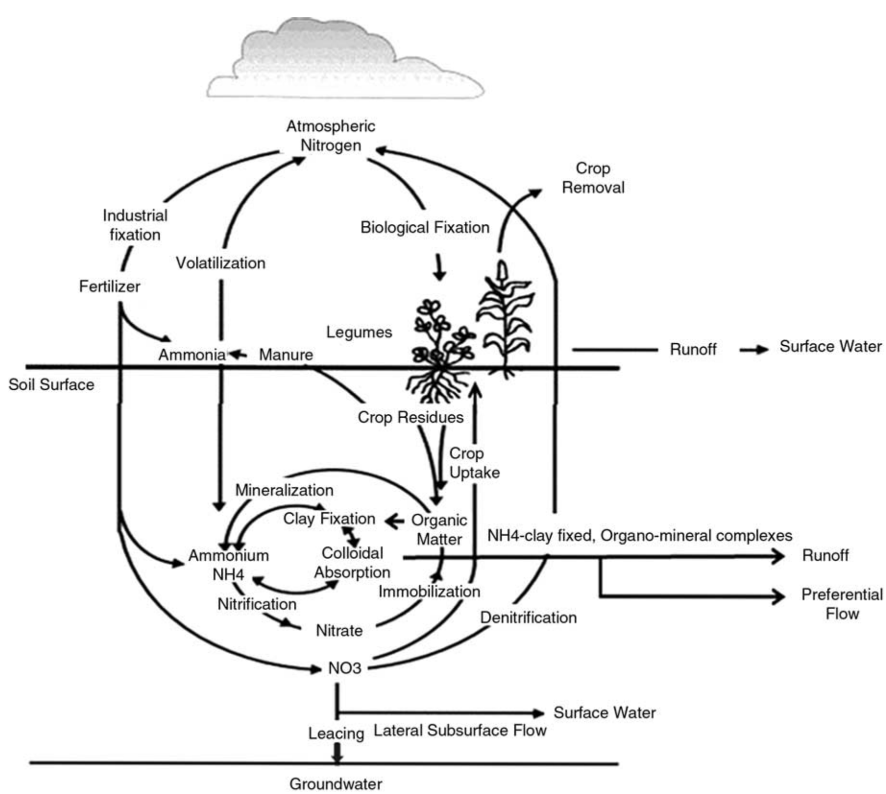

Fig. 1. Nitrogen cycle in an agroecosystem (modified from National Research Council 1993).

Loss of PON is expected to be lower in runoff from no-till soil than moldboard-plowed soils. Horne et al. (1992) reported that no-tillage resulted in the lowest infiltration rates compared to moldboard plowing and conventional tillage on a silt loam during a 10-yr study. Azooz and Arshad (2001) measured significantly lower infiltration rates under conventional tillage than no-tillage on silt and sandy loam luvisols of the northwestern Canadian prairies. Therefore, the impact of no-tillage on infiltration and loss of PON shows mixed results, but the tendency is that no-tillage increases macropore connectivity when compared to conventional tillage practices. This corresponds to a general increase in infiltration rates for no-tillage (Strudley et al. 2008) and thus less PON loss in surface runoff. However, more sediment and thus sediment-associated N could be lost under conservation tillage due to the greater connectivity between macropores and tile drains. For example, Zhao et al. (2001) found a fourfold greater sediment loss in tile drains under ridge tillage than moldboard-plowed soils.

No-tillage increases soil aggregation and the formation and stabilization of microaggregates within macroaggregates; therefore, the protection of SOM is increased, resulting in slower turnover rates (Six et al. 1999). Some studies reported enhanced SOM mineralization in no-tillage systems as crop residues that remain on the soil surface have a priming effect, which stimulates N mineralization (Bruulsema and Christie 1987) and contributes to the RSN pool. In most cases, decay rates of residues left on the soil surface are slow compared to residues that are incorporated in moldboard-plowed soils (Beare et al. 1994; Parton et al. 1994). However, surface residues appear to decay rapidly when moisture and nutrients are not limiting (Scott 1996; Alvarez 1998).

In Quebec and Ontario, the common tillage practice in corn fields is primary tillage (moldboard plowing) in fall and secondary tillage (harrowing) in spring. Although fall moldboard plowing enhances soil drying and warming the following spring (Zhao et al. 2001), its most pronounced effect is on the reduction of residues and organic matter on the soil surface. Therefore, it is expected that less N will be lost via surface runoff in moldboard-plowed soils in this region, whereas conservation tillage systems, including no-till, will promote N loss through subsurface processes.

Crop Selection

Production of high-yielding crops in Quebec and Ontario requires careful selection of crop species and cultivars that are adapted to the local soil and climatic conditions. While fertilization is necessary to optimize yield and quality, this practice may contribute to pollution of surface waters. The risk of NO_3-N leaching is generally higher in shallow-rooted crops that have low fertilizer N use efficiency, particularly when grown on coarse-textured soils with high inputs of N fertilizer. For example, high NO_3-N leaching losses are common in potato production systems on sandy soils receiving up to 200 kg N ha^{-1} in banded fertilizer applications (Zebarth and Rosen 2007). Soil NO_3-N concentrations measured at a 0.30 m depth in spring from 228 commercial potato fields in New Brunswick ranged from 3 to 100% of soil NO_3-N at harvest in the preceding fall, indicating that significant leaching occurred between fall and spring (Zebarth et al. 2003). Since the RSN leaching in conventionally managed potato production systems can be substantial (e.g., 116 kg NO_3-N ha^{-1} of a 177–303 kg NO_3-N ha^{-1} fertilizer N input) (Gasser et al. 2002), farmers should be aware of options to reduce the RSN, which are discussed the next sections.

In addition, uptake of N by some crops (e.g., vegetables) increases during the mid-season period (Magdoff 1991) and additional N fertilizer is required. Applying N fertilizer at this time increases the potential for in-season NO_3-N leaching (Hartz et al. 2000).

Crop Rotations

Crop rotations have a role in controlling N loss from agroecosystems. Corn production, which covers 1.4 million ha in Canada and occurs mainly in southern Ontario (50% of total area of corn) and Quebec (35% of total area of corn) (Statistics Canada 2007), is an example of a crop with high N demand that is met partly from the soil N supply and partly from N fertilizer inputs (Cassman et al. 2002; Ladha et al. 2005). The RSN in soils under corn production is in the order of 25–40 kg N ha^{-1} (De Jong et al. 2007) and is susceptible to loss through the pathways described earlier. Nitrogen loss in a tile-drained field in Ontario was highest with continuous corn, intermediate with a corn–oat–alfalfa–alfalfa rotation, and lowest with continuous bluegrass (*Poa compressa*) (Bolton et al. 1970). This was attributed to the fact that continuous corn receiving N fertilizer inputs of 160 kg N ha^{-1} each year caused to a build-up of RSN. Growing corn in rotation, however, depleted soil mineral N reserves because oats received less N fertilizer and alfalfa received none at all, relying on N_2 fixation and the soil N supply to meet plant N requirements. Cumulative NO_3-N loss through tile drainage from a clay–loam soil in southwestern Ontario after 3 yr was 82 kg N ha^{-1} for fertilized continuous corn, 100 kg N ha^{-1} for fertilized rotation corn (corn–oat–alfalfa–alfalfa), and 70 kg N ha^{-1} for second-year fertilized alfalfa (Tan et al. 2002b). It should be noted that the N fertilizer input was the same for continuous corn and corn planted after plow-down of the alfalfa crop. If an appropriate N credit had been given for alfalfa residues, this would likely have reduced NO_3-N loss from the rotation treatment. In conclusion, incorporating crops that use RSN in the rotation and accounting for the N released from decomposing crop residues (particularly leguminous crops) is expected to reduce soluble N leaching between growing seasons.

Fertilization

Non-leguminous crops grown in Quebec and Ontario require N fertilizer inputs to achieve economic yields because mineralization of soil organic N in a humid climate is insufficient to meet the N requirements. Among mineral fertilizers, ammonium-based fertilizers are the most widely sold in North America because of accessibility and cost (Canadian Fertilizer Institute 2007; United State Department of Agriculture 2008). Hong et al. (2007) reported that half of applied fertilizer N was taken up by corn, immobilized as SON or leached from the soil during the growing season, while the other half remains as RSN. Zhang et al. (2004) found high NO_3-N leaching losses during spring rainfall events and greater risk of surface water pollution from corn farms in Quebec due to high levels of RSN from the previous cropping year. Mitsch et al. (2001) concluded that applying appropriate amounts of fertilizer N can reduce RSN and its subsequent loss from cropping systems to surface water. According to Vinten et al. (1994), the leaching of NO_3-N is weakly correlated to fertilizer application rate when crop demand for N is high. Altering the rate of N fertilizer to match crop N demand is therefore a necessary first step in improving on-farm economic benefits and preserving water quality in the environment.

Manure is also available on many farms in Quebec and Ontario and can be applied as a sole source of N fertilizer or in conjunction with mineral fertilizer. Manure contains 50 to 80% of the N originally present in the animal feed, depending on the type of livestock and feed (Chambers et al. 2001). The organic N fraction of manure varies between manure types and represents from 14 to 99% of the total N content (Chadwick et al. 2000). When most of the N in manure is in the organic form, it is not immediately available to crops, but becomes available gradually as decomposition occurs. In an Ontario field study, Jayasundara et al. (2007) found that 45–69% of applied manure N was present in the soil after harvest and N mineralization continued until soil freezing. This implies that over-winter N losses are more likely from a manured field than one receiving inorganic N fertilizer, given equal application rates of total N.

Water Management Structures

Grassed waterways reduce surface runoff volume and velocity, by increasing roughness of the soil surface and improving the infiltration (Borin et al. 2005; Deletic and Fletcher 2006). Consequently, decreasing flow volume and velocity and increasing water infiltration from the soil surface will reduce soluble and particulate N transport. Another water management structure to reduce surface runoff is terracing in combination with grassed waterways (Daigle 1983). In rolling landscapes with 5 to 9% slope, terraces break long slopes into shorter segments and safely dispose of runoff through grassed waterways (Chow et al. 1999).

Riparian buffer strips are also beneficial in reducing soluble N and PON transport in surface runoff. Riparian buffers can remove soluble N from overland flow by uptake and storage in vegetation, microbial immobilization and storage in the soil as organic nitrogen and microbial conversion to gaseous forms of nitrogen (denitrification; Weller et al. 1994). Mander et al. (1997) reported NO_3-N removal capacities of riparian buffers as high as 964 kg ha^{-1} yr^{-1} due to high denitrification rates. The capacity of riparian buffers to reduce soluble and particulate N depends upon its width, species composition and vegetation management (Broadmeadow and Misbet 2004). Recommended widths are between 5 and 30 m. Narrow buffer strips are unlikely to provide inadequate protection of aquatic systems and too wide buffers reduce the area of cropland (Broadmeadow and Misbet 2004). Schmitt et al. (1999) compared the performance of several vegetative strip designs (different types of plant cover and strip widths) in reducing contaminant losses in runoff and drainage water. These authors found that 7.5 m and 15 m wide grass strips reduced sediment losses by 76 and 93%, respectively, while NO_3-N movement decreased by 24 and 48%, respectively. Mander et al. (1997) and Snyder et al. (1998) investigated the filtering efficacy of riparian forest buffer strips and found that young treed strips have a greater capacity than buffer strips with older trees to retain N. Grazing of riparian area vegetation can lower soil infiltration rates and increase runoff, erosion, and sedimentation (McGinty et al. 1979; Self-Davis et al. 2003). The effectiveness of filter strip systems is often low in the first year after establishment because of the limited vegetation cover. In conclusion, the effectiveness of these systems in reducing N loss in surface runoff is field-specific and may vary according to the width of strips and type of filter vegetation. Tile drainage improves infiltration and prevents soil erosion and can be effective in reducing soluble and sediment associated N loss via surface runoff (Gaynor et al. 1995).

Tile drainage is a subsurface conduit, made of fired clay, concrete or perforated corrugated plastic that removes excess water from the soil profile. In Quebec and Ontario, approximately 2 million ha of cropland has tile drainage (Helwig et al. 2002). In the Pike River watershed, which drains into the Missisquoi Bay of Quebec, 44% of the cultivated area has tile drains (CBVBM 2003). In Ontario, tile drains are installed on about 60 to 70% of agricultural lands under corn and soybean cultivation (McKague et al. 2006). Tile drainage reduces anoxia and associated denitrification in soils and reduces the contact between runoff water and oxic soils or riparian areas (McIsaac and Hu 2004; Royer et al. 2006; David et al. 2010). Other studies have clearly demonstrated that tile drainage facilitates transport of soil pore water (Beauchemin et al. 1998), which results in a greater proportion of N being lost via this pathway.

Water table management is an agricultural practice that was reported to improve water quality while maintaining and increasing crop yield (Kalita and Kanwar 1993; Drury et al. 1996; Cooper et al. 1999). Water table management includes controlled drainage (CD) and subirrigation (SI). Under CD, the level of water in the outlet is raised so that water is retained within the tile drains rather than draining freely. No supplemental water, other than rainfall, is added to the system. Studies showed that CD is an effective method for retaining crop-available water and dissolved nutrients in the root zone (Wesström and Messing 2007). Gilliam et al. (1979) observed that CD reduced annual NO_3-N in drainage water by 50% from a poorly drained soil in eastern North Carolina. Water table management structures may therefore reduce N loss from tile drains, but the extent of their use is not known in Quebec and Ontario.

Subirrigation involves pumping supplemental water into a controlled drainage system to maintain the water table at a designed level during drought periods. This system is used during dry summer months when rainfall is insufficient to maintain soil moisture at an adequate level (40–60 mm of water every 10–14 d) for field crop production on clayey soils (Tan et al. 1999). Subirrigation is possible on relatively flat lands, where soil type and conditions permit the easy movement of water from the water table to the root zone via upward flux or capillary rise. It is practiced in some parts of Quebec and Ontario.

Controlled drainage-subirrigation (CD-SI) serves a dual function of controlling drainage outflow during periods of excess water and injecting water back into tile drains during dry periods (Tan et al. 1999). This method of water table management reduces NO_3-N pollution either by restricting the volume of drain discharge (Gilliam and Skaggs 1986; Wright et al. 1992; Kliewer and Gilliam 1995) and/or by creating anaerobic conditions that enhance denitrification (Elmi et al. 2000; Jacinthe et al. 2000). More NO_3-N reduction can be achieved if CD also operates during the early spring when the soil is more susceptible to N loss (Patni et al. 1998) and there is no crop present in the field. However, high water tables in the spring would make many fields untrafficable and is undesirable for farms in Quebec and Ontario where cold wet soil conditions already impede timely planting of annual crops.

Installation of tile drains at shallower depths (e.g., 0.75 m to 1.0 m) can reduce the height of the drainage outlet (Skaggs and Chescheir 2003). Such an installation is analogous to CD, reducing drainage outflows and increasing deep seepage (Burchell et al. 2003). The result is a saturated zone below the tile depth that promotes denitrification and reduces NO_3-N losses in drainage outflows. Using such a system, Gordon et al. (1998) found a reduction of 34% in NO_3-N losses in tile drainage water. Contrary to these findings, Burchell et al. (2003) reported no difference between NO_3-N export in shallow tile drainage (0.7–1 m) and deep tile drainage (1–1.5 m) on a clayey soil.

REGULATIONS, INTERVENTIONS AND POLICIES TO REDUCE RESIDUAL SOIL NITROGEN LOSSES FROM AGROECOSYSTEMS IN QUEBEC AND ONTARIO

There is no question that the climate and hydrologic conditions in Quebec and Ontario make agricultural soils vulnerable to N loss. Recognizing the link between high RSN and high N loading of water bodies, the Quebec and Ontario governments have developed guidelines and regulations aimed at reducing RSN accumulation in agroecosystems. In addition to legislation, a number of interventions and policies have been adopted to protect water quality in these provinces. Best management practices, environmental farm plans (EFPs) and agricultural subsidies for modernizing farm operations are examples of government- and producer-led initiatives to control N pollution from farms, and are discussed in the next sections.

Agricultural Regulations for Controlling Non-Point Sources of Nitrogen Pollution from Farms

In Quebec and Ontario, the provincial ministries of agriculture and environment collaborate to devise regulations that support crop production, maintain environmental health and protect surface water quality. In Quebec, the Agricultural Operations Regulations are used for soil and water protection in agricultural environments. These regulations came into force on 2002 Jun. 14 and were revised from 1997 regulations aimed at reducing pollution from agricultural sources. The regulations are based on P requirements for plant growth and the P saturation capacity of soils. Although they are based on manure-P management, producers following the regulation will probably keep N inputs at acceptable levels so that concentrations in surface water bodies affected by agricultural activities do not exceed the limit of 1.1 mg total N L^{-1} proposed by Chambers et al. (2012). This assumption is based on the fact that the N:P ratio of manure is fairly constant at 1:3 to 1:4 (Kellogg et al. 2000). Using a mass balance approach, producers are required to calculate the annual P inputs to farm fields from livestock manure, fertilizer and other sources, and cannot exceed P application limits set for particular crops and soils.

Ontario initially laid out legal requirements for the storage and handling of manure and other nutrients under the Nutrient Management Act (NMA). This regulation was developed by the Ministry of the Environment and the Ministry of Agriculture and Food in 2002 as part of the government's Clean Water program. The regulations control the storage, handling and application of nutrients to cropland. According to these regulations, if more than one type of nutrient source is stored on site, the nutrients must be managed in accordance with the most restrictive requirement for the most vulnerable nutrient source.

Best Management Practices for Reducing Residual Soil Nitrogen Loss from Agroecosystems

Best management practices are guidelines intended to minimize the impact of agricultural activities on soil and water resources while maintaining productivity [Food and Agriculture Organization of the United Nations (FAO) 2006]. Results from the 2006 Farm Environmental Management Survey (FEMS) showed that producers across Canada employed a number of BMPs to manage manure, fertilizers and pesticides, and protect land and water resources (Environment Canada 2010). This section will focus on the BMPs designed to minimize RSN. The BMPs expected to be effective in reducing soluble and particulate N pools lost from agroecosystems are illustrated in Fig. 2.

Tillage

Conservation tillage in fall limits soil disturbance by keeping at least 30% of crop residue on the soil surface. This BMP can increase infiltration and reduce soil erosion and runoff, which in turn can reduce the loss of RSN through surface transport processes (Sprague and Gronberg 2012). In a 5-yr study, no-till soils increased tile drainage volume by 48% and soluble N loss by 29% (82.3 kg N ha^{-1}) compared with tilled soils, which lost 63.7 kg N ha^{-1} in soluble N (Tan et al. 2002a). Under certain conditions, conservation tillage may not be effective in reducing N loss. For example, surface application of fertilizer or manure in no-till fields may promote N loss in runoff, particularly if spring NO_3-N levels are high at the time that spring snowmelt occurs in Quebec and Ontario. No-till may reduce particulate N but not soluble N losses (Gassman et al. 2006). Dinnes et al. (2002) found that no-till had greater subsurface drainage flow than the conventional tillage, but NO_3-N losses were marginally greater (about 5%) with conventional tillage. They concluded that NO_3-N losses through tile drainage depend more on growing-season precipitation than on tillage.

Vegetation

Planting catch crops in August–September after the higher-value main crop (grown April–August) has been harvested can reduce the RSN pool (Thorup-Kristensen et al. 2003; Strock 2004). In this BMP, the catch crop utilizes N not used by the main crop or that is mineralized during the fall growing period. Having vegetative cover on the field can further reduce both soil surface erosion and particulate-associated N (e.g., PON) concentrations in runoff during the fall and following spring. Winter cover crops reduced late fall NO_3-N concentrations in tile drainage from a variety of systems (Guillard et al. 1995; Philips and Stopes 1995). Staver and Brinsfield (1998) also reported a reduction of 54% in total N load from tile drainage when a winter rye (*Secale cereale*) cover crop was planted after corn. However, plow-down of these residues may either increase or decrease spring NO_3-N levels, depending on the extent of N immobilization in the crop residue (Wegger and Mengal 1988).

Intercropping or using rotations in which crop residue N is used to reduce fertilizer N input is an effective way to reduce NO_3-N loss from agroecosystems (Ofori and Stern 1987; Hesterman et al. 1992). For example in a corn–soybean rotation, soybean does not receive fertilizer N and accumulates N through soil uptake and biological fixation of atmospheric N. Soybean uptake of residual N following corn may increase fertilizer recovery and decrease potential N leaching losses (Gentry et al. 1998). In an experiment in Ontario, cumulative NO_3-N leaching loss was reduced by 51% from 133 kg N ha^{-1} in conventional practices to 68 kg N ha^{-1} when applying a 30 kg N ha^{-1} credit for soybean residue from the previous year, as well as using cover crops such as red clover where possible (Jayasundara et al. 2007).

Agroforestry systems in which trees extract water and nutrients from greater depths than most agricultural crops are also effective in reducing NO_3-N loss via leaching (Van Noordwijk et al. 1996). Thevathasan (1998) showed that NO_3-N leaving crop-tree (barley–poplar) intercropping sites in Ontario was reduced by an estimated 50% compared to a conventional monocropped field.

Fertilization

The BMPs used to improve N fertilizer use efficiency are among the least costly practices and are helpful in reducing RSN and mitigating N losses from agroecosystems. Improving N management by properly accounting for significant sources of available N, including N added in animal manure and crop residues, and mineralization of soil organic matter, to reduce N fertilizer inputs is a simple and effective BMP that can reduce fertilizer costs on farms (FAO 2006). For example, it was suggested that no more than 75% of the crop N requirement in a single year should come from manure since the organic N will contribute to RSN (FAO 2006).

Careful synchronization of N fertilization with key growth stages is important to maximize N use efficiency. Whenever possible, N fertilization must be avoided during periods when the potential for leaching is high. Smiciklas and Moore (2004) reported that fall application of anhydrous ammonia N resulted in a 50% increase in NO_3-N loadings of subsurface drainage water when compared with the same rate of N applied in the spring. Jaynes et al. (2004) indicated that late spring application of N fertilizer could significantly reduce required N applications when compared to standard (pre-plant N application) practices followed by farmers. Soil NO_3-N concentration at pre-plant stage represents residual soil NO_3-N from the previous growing season (Zebarth et al. 2009). Adoption of late spring applications could also reduce the NO_3-N

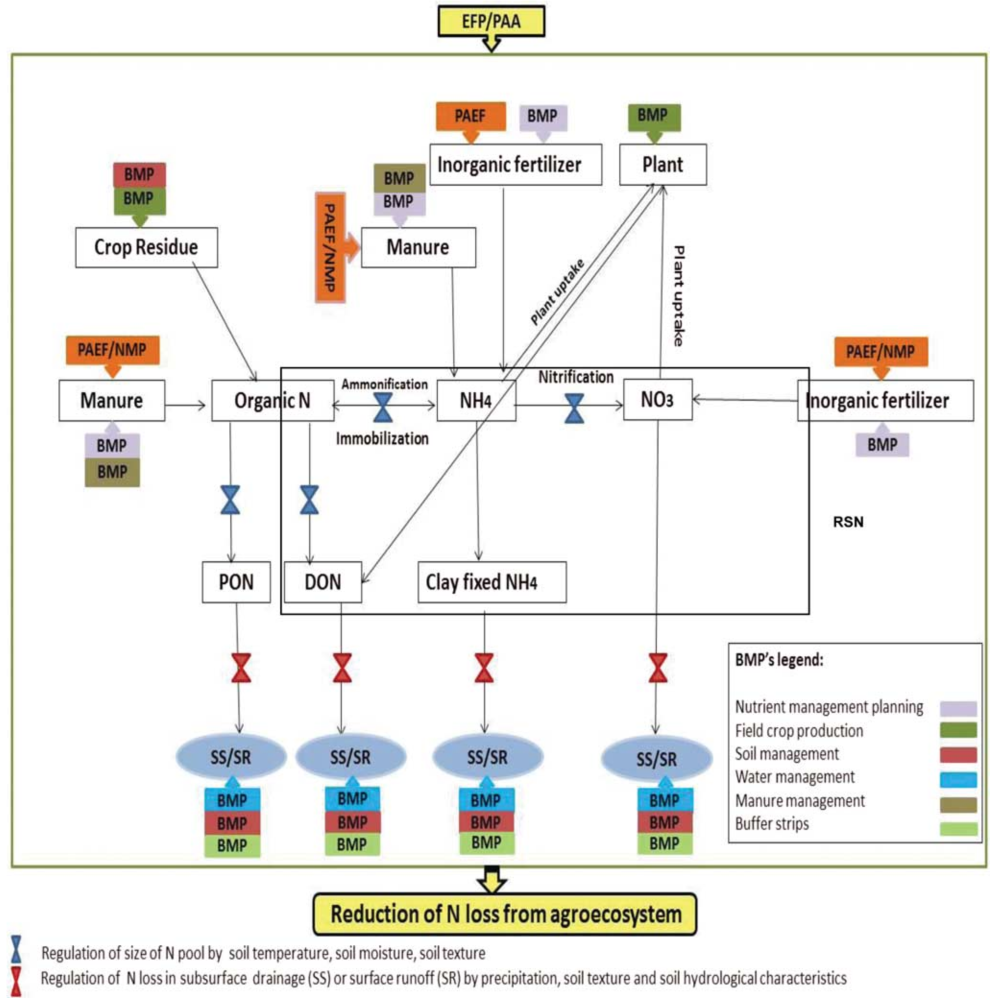

Fig. 2. Conceptual model of control points for nitrogen losses from agroecosystems.

concentration in surface runoff by 30% compared to pre-plant application (Jaynes et al. 2004).

Further improvements in fertilizer use are expected with the development and standardization of soil N tests for humid regions. The pre-sidedress soil NO_3-N test for corn is calibrated to adjust N fertilizer inputs in Ontario, but there is no comparable test for other crops grown in Ontario, nor is there a standard soil N test available for use in Quebec. A soil N test that considers the amount of plant-available N at seeding and predicts the soil N supply during the growing season is needed to achieve better N fertilizer recommendations in this region. In this regard, a combination of N indices that are best suited for the particular system in conjunction with weather forecasts can be used (St. Luce et al. 2012). Kay et al. (2006) and Dessureault-Rompre et al. (2010) also showed that integrated soil and climatic parameters can explain variation in soil N supply. For example, early-season rainfall exerted a greater impact on N supply than rainfall later in the season, so N fertilizer recommendations could be adjusted based on early season weather conditions. Eventually, the soil N test could be automated with on-site sensor technology to achieve adjustable rate N fertilizer applications in site-specific agriculture (Erhart et al. 2005; Grigatti et al. 2007).

Surface Runoff

Buffer strips are vegetated areas at the edges of fields that intercept runoff before it enters local water ways, allowing slow percolation through the buffer, infiltration into the ground and removal of sediment and N (Hubbard et al. 1998; Snyder et al. 1998). Peterjohn and Correll (1984) reported an 89.7% reduction in suspended particles and a 60.4% reduction in NO_3-N concentrations of runoff water passing through a 19 m vegetated buffer. Xu et al. (1992) found that concentrations decreased from 764 mg to 0.5 mg N kg^{-1} soil within the first 10 m of the buffer area.

Grassed waterways are another BMP that can be used alone or in conjunction with diversion terraces and are typically constructed in natural depressions where water would normally flow and collect. Excess runoff drains into grassed waterways and the structure traps sediment and nutrients moving into the waterway from surrounding agricultural lands (Agriculture and Agri-Food Canada 2010). The vegetation also stabilizes the banks and shores from the erosive action of the streamflows. An experimental study in southern Quebec showed that grassed waterways reduced runoff water volumes by 40%, total suspended solids by 87%, and NO_3-N by 33% (Duchemin and Hogue 2009).

Drainage

Skaggs et al. (1982) proposed tile drainage as a BMP for reducing erosion on flat lands. Another BMP that is effective in reducing N loads in surface water is a CD system, by reducing NO_3-N leaching by 40 to 90% in tile-drained land (Meek et al. 1970; Doty et al. 1986; Belcher and Fogiel 1991; Madramootoo et al. 1992; Madramootoo 1994; Drury et al. 1996; Tan et al. 1998, 1999). Drury et al. (1996) found a reduction of 43% in annual NO_3-N losses from CD compared with conventional drainage. In a sandy loam soil in southwestern Ontario, Ng et al. (2001) reported that the flow weighted mean NO_3-N concentration of the drainage water was reduced by 70% from 19.2 mg N L^{-1} for free tile-drained soil to 11.3 mg N L^{-1} for a CD-SI system. Nitrate losses were better controlled with a CD system in conjunction with conservation tillage. However, as water limitations are reduced by CD and CD-SI, this may result in N limitations for crop growth and so crops may need additional N fertilizer to maximize yield. Tile drainage reduces surface runoff by increasing water infiltration, thereby increasing soluble N movement through the soil profile (Drury et al. 2001). Consequently BMPs such as a balanced N fertilization and installation of biofilters to the tile drain outlet to intercept and remove NO_3-N lost from fields may also be needed to mitigate N loss to waterways (Schipper et al. 2004; Su and Puls 2007). These subsurface systems depend on microbial denitrification to mineralize and remove NO_3-N. Since denitrification is an anaerobic process, it requires an adequate supply of available carbon, such as wood chips or sawdust for these systems to function properly (Greenan et al. 2006; Vymazal 2007).

Single BMP vs. Multiple BMPs

The reduction of N loss from agricultural fields is unlikely to be solved with a single BMP. While a single BMP may be effective in reducing the loading of a specific form of N into the surface water, it could have no effect or even increase the transport of other N forms. For example, cover crops can reduce sediment loads but can increase water movement through the soil profile and therefore contribute to dissolved N losses through drainage (Martel et al. 2007). Also, hydrological characteristics of the agricultural system (soil hydraulic properties, topography, vegetation, etc.) can influence the BMPs' impact on size and chemical composition of the RSN pool, as well as the pathway by which RSN is lost. Moreover, in an agricultural watershed with multiple farms, it is challenging to choose the right combination of BMPs that provide maximum reduction of N loss at the watershed scale with a reasonable cost of implementation. The selection of multiple BMPs should be optimized to achieve maximum reduction in N loss at minimum cost to the producer (Maringanti et al. 2011).

A study in the Walbridge basin of the Missisquoi Bay watershed examined the effect of multiple BMPs on the sediment and N export to surface water (Michaud et al. 2008). More than 60% of the land is dominated by annual crops such as grain corn and the upstream portion of the basin also has proportionately more swine and poultry operations. Michaud et al. (2008) tested scenarios that combined BMPs to reduce N, P and suspended solid loadings into surface water, and compared them with a single baseline scenario. Overall, multiple BMPs were more advantageous than a single BMP, although the multiple BMPs did not necessarily interact in a synergistic manner (positive interaction) or even a cumulative manner (neutral interaction) in relation to a given water quality parameter (i.e., sediment, N and P). In practice, the effect of multiple BMPs varied according to the water quality parameter considered, but a few BMPs emerged as highly promising for reducing non-point source nutrient pollution and sediment loading in the Wallbridge basin. For example, the introduction of no-till farming in grain corn fields generated substantial reductions in sediment, N and P exports. Another positive outcome was the estimated 54% reduction in N export when N fertilizer was incorporated immediately (within 24 h) and cover crop BMPs were adopted, compared with the baseline scenario (conventional tillage practices with fall plowing and spring manure applied in the pre-plant period).

Putting It All Together: Environmental Farm Plans

As discussed in the previous sections, the size of the RSN pool and amount of N loss are regulated by a number of factors including soil characteristics (Fig. 2). Since soils and other site-specific characteristics (e.g., cropping systems, tillage practices, fertilizer sources and application methods, water management structures) are different on individual farms, the nutrient management program and BMPs should be considered for site-specific conditions to ensure that the practices function together to achieve the overall agri-environmental goals. To help producers identify and address site-specific risks to the environment, Ontario and Quebec created voluntary, confidential educational programs that help producers develop environmental action plans for their farms. Ontario's program is the Environmental Farm Plan

(EFP) program, started in the 1990s. Quebec's program is the agri-environmental support program (PAA) that was initiated in 2004 to support the adoption of improved agricultural practices on farms.

An EFP/PAA starts with an agri-environmental profile of a farm, including an assessment of practices related to regulations and BMPs. The EFP/PAA is then completed by identifying BMPs that can solve particular problems, determining which ones to implement and setting a time schedule for action. In the next step, the farmer will implement the EFP/PPA plan. The actions on farms will be evaluated by the farmer and government-certified consultants trained to help producers to complete EFPs/PAAs. Outcomes resulting from the implementation of BMPs are summarized in annual activity reports. The EFP/PAA helps the farmers identify the strengths and weaknesses of their operation in protecting the environment, and is an effective tool for selecting and implementing appropriate BMPs to reduce RSN and control N loss from their farms.

Incentives and Policies for Reducing Residual Soil Nitrogen Losses from Agroecosystems

Although farmers are becoming aware of the importance of soil management, water quality and storage of manure, the number of farmers who participate in EFPs in Ontario indicates that around 38% of participants took no further part in the scheme (Robinson 2006) and only 38.4% of growers (23 000 applicants) participated in workshops by 2003. From 2004 to 2008, the number of Agri-Environmental Advisory Clubs (AEAC) member farms in Quebec that adopted Agricultural Operations Regulations actions like spreading liquid livestock manure with a boom sprayer increased from 29 to 60%, while those that installed barriers to prohibit livestock access to streams increased from 63 to 76% (Agri-environmental Advisory Clubs 2009).

This situation clearly illustrates the need to increase grower participation in EFPs in Quebec and Ontario. Lobley and Potter (1998) and Wilson (1997) identified the lack of EFP compatibility with ongoing farm management plans, financial reasons and lack of information about government guidelines as reasons for non-participation in EFPs. Other determinants are the presence and absence of a successor for the farm (Brotherton 1990), the quality of the information provided on guidelines (Cundliffe 2000) and peer pressure (Wynn et al. 2001). Between 1993 and 2009, 35 400 farm businesses in Quebec participated in PAA workshops at least once, and about 28 500 projects were completed by more than 17 000 farmers. Factors that supported BMP adoption were education, proven practices, regulation and peer pressure (Agri-environmental Advisory Clubs 2009).

Many farmers avoid BMPs because they feel that using less N fertilizer or manure, reducing tillage intensity, or making other changes in their practices will reduce in farm income. Therefore a guarantee against any potential loss of income as a result of BMP adoption can be a helpful incentive. This can be achieved by compensating farmers if yield and income were reduced while participating in EFPs. A number of municipalities, conservation authorities and other organizations across Ontario offered financial incentives to farmers to support on-farm environmental improvements. For example, the Christian Farmers Federation of Ontario (CFFO) established an Ontario Environmental Initiative Loan Fund Program such that farmers were eligible to receive loans when they prepared an EFP Action Plan (Robinson 2006).

An example of non-financial incentives was the Ontario Stewardship program. Initiated by Ontario's Ministry of Natural Resources (OMNR) in 1995, this program encouraged growers to be good stewards of their lands. The program provided encouragement via education, collaborative arrangements and peer networking amongst 39 Community Stewardship Councils, which received financial support from the OMNR (Robinson 2006). The benefits of this program for the farmers were identified as transfer of knowledge, broadening and strengthening of their chain of contacts, and greater access to key agencies and associations.

Increasing the environmental awareness among Quebec producers and supporting them in their agri-environmental efforts can be achieved via "accompanying measures". These include: knowledge enhancement initiatives (soil degradation inventories, environmental monitoring, agri-environmental portraits), education, training, and technology transfer activities (State of the St. Lawrence Monitoring Committee 2008), as well as financial assistance programs to help them achieve regulatory compliance, especially for liquid manure storage structures.

CONCLUSION AND PERSPECTIVES

Considerable progress has been made in recent years to improve nutrient management practices and reduce N losses from agroecosystems. Despite such advances, N loss to the aquatic ecosystems is still above the acceptable limits for water quality protection. Research is still needed to identify sources of N in waterways, and to determine whether N losses can be controlled with BMPs. To improve the efficiency of N fertilizer use, accurate site-specific estimates of N mineralization rates of organic N in manure, crop residues and SOM are needed. Careful accounting for N from all inputs, including soil-based N credits and N credits for legumes and manure inputs in previous years should be included. Soil testing for N is also recommended, although test methods remain to be standardized and calibrated in relation to N fertilizer requirements for crops grown in Quebec and Ontario. Further research on the effect of multiple BMPs on RSN accumulation and loss from agricultural fields is necessary. Encouraging growers to participate in agri-environmental clubs and publicizing "success stories" will have a positive impact on the adoption of BMPs. Financial incentives and better communication between growers, agro-environmental advisors, provincial and federal organizations are also expected to be beneficial for the implementation of BMPs for reducing RSN, thereby mitigating soluble and particulate N losses from agroecosystems in Quebec and Ontario.

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