

Chapter 14

Nitrous Oxide Emissions from Potato Production and Strategies to Reduce Them

David L. Burton, Bernie J. Zebarth, John A. McLeod,
and Claudia Goyer

Abstract The potato production system provides an interesting environment to examine denitrification and nitrous oxide (N_2O) emissions. Tillage is used to form ridges of topsoil in which the potato plant and fertilizer are placed. The tillage operation results in a low bulk density within this ridge resulting in a well-aerated environment rich in carbon (C) and nitrate (NO_3^-) in contrast with the compact furrow that remains between the ridges. We review the soil factors that control denitrification and N_2O emissions within the context of rain-fed potato production systems in Atlantic Canada. Further, we examine the role of water content in controlling denitrification and N_2O emissions at different spatial scales: the ridge-furrow complex, soil profile and landscape scales. While denitrification is found to predominate in the compact and wet furrow environment, N_2O emissions are greatest in the potato ridge as a result of the greater C and NO_3^- concentrations found there. Water movement at larger spatial scales results in a shift of N_2O production to deeper in the soil profile and to lower slope positions in the landscape. Beneficial management practices (BMPs) for reducing N_2O emissions from rain-fed potato production include improved fertilizer N management (placement and timing), choice of crop rotation, manure management and drainage. It is important to realize, however, that because of the complex controls on denitrification and N_2O emissions, the effects of different BMPs on N_2O emissions can vary with soil properties and climatic conditions.

D.L. Burton (✉)

Nova Scotia Agricultural College, P.O. Box 550, Truro, NS, Canada B2N 5E3
e-mail: dburton@nsac.ca

B.J. Zebarth • C. Goyer

Potato Research Centre, Agriculture and Agri-Food Canada, , 850 Lincoln Rd.,
P.O. Box 20280, Fredericton, NB, Canada E3B 4Z7

J.A. McLeod

Crops and Livestock Research Centre, Agriculture and Agri-Food Canada,
440 University Ave., Charlottetown, PE, Canada C1A 4N6

14.1 Introduction

Changes in the global climate system have been linked to anthropogenic emissions of greenhouse gases (GHG) (IPCC 2007). In 2008, 8.4% of the total GHG emissions reported in Canada resulted from agricultural activities (Environment 2010). Nitrous oxide (N_2O) from agricultural soils accounted for 50% of the anthropogenic GHG emissions from Canadian agroecosystems. In addition to being a greenhouse gas, N_2O is also responsible for stratospheric ozone depletion (Crutzen and Ehhalt 1977). Nitrogen fertilizer, the major source of agricultural N_2O emissions, has been instrumental in increasing yield from arable cropping systems over the past 50 years (Matson et al. 1997; Tillman et al. 2002). Potato is the dominant arable crop in Atlantic Canada. Large fertilizer N inputs, frequently 200 kg N ha^{-1} or more, are applied to the potato crop to achieve the tuber yield and size distribution demanded by the potato processing industry (Zebarth et al. 2003; Zebarth and Rosen 2007). These large N inputs raise concerns as to the potential for increased N_2O emissions (Zebarth et al. 2009a).

The potato production system is an interesting one from the perspective of N_2O emissions. As with other ridge/furrow management production systems, soil management practices cause distinct distributions of soil physical, chemical and biological characteristics over relatively short distances. The potato ridge, formed as a result of tillage, provides a low bulk density, well-aerated environment suitable for the formation of tubers (Fig. 14.1). In Atlantic Canada, the ridge is commonly formed when the plants are 15–30 cm tall, but there is a trend towards earlier ridge formation that can occur anytime from planting to emergence. The majority of the fertilizer application in Atlantic Canada is as a band application at planting placed adjacent to the seed-pieces in the potato ridge. The potato furrows by contrast have a greater soil bulk density and therefore less aerobic environment where carbon and nitrate (NO_3^-) supplies are reduced relative to the ridge. In Atlantic Canada the majority of the A horizon, the horizon in which organic carbon accumulates, is used to form the ridge. The furrow consists of a thin layer of A horizon (maximum of 5 cm) that remains after tillage overlying a B horizon or in some cases C horizon. In Atlantic Canada the soils tend to be rather shallow soil with low pH and frequently have compact subsurface horizons making the distinction between ridge and furrow even more dramatic. The furrow is also a region of water accumulation as a result of the runoff of precipitation. This substantial variation in soil physical and chemical properties over a short distance has the potential to result in markedly different soil N processes and microbial communities. In this chapter we will use the results of studies we have conducted in rain-fed potato production in Atlantic Canada to examine the controls on N_2O emissions from potato production systems and strategies for managing these emissions.

14.2 Factors Controlling N_2O Emissions

The biological production of N_2O in agricultural soils occurs primarily as a result of the processes of nitrification and denitrification (Firestone and Davidson 1989; Mosier 1998). The conditions that favor these processes are very different. Nitrification, the

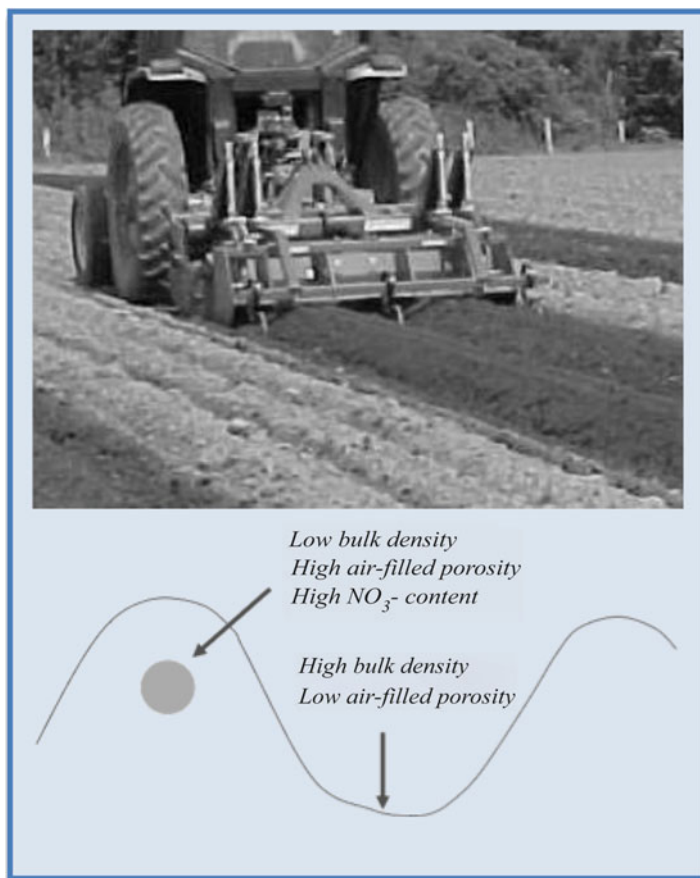


Fig. 14.1 The ridge-forming operation results in the formation of a low bulk density ridge that contains higher NO_3^- due to banded fertilizer application, and higher organic carbon concentrations because most of the C-rich surface horizon is located in the ridge, compared with the furrow. The hilling operation can occur at different times, but is commonly done in eastern Canada when the plants are 15–30 cm high

oxidation of ammonium (NH_4^+) to NO_3^- , occurs as a result of the activity of autotrophic organisms in aerobic soils. Denitrification is a respiratory process whereby heterotrophic organisms respire oxides of N in the absence of O_2 , producing N_2 as the final product. As a result, denitrification generally occurs in moist soils where O_2 supply is reduced. For this, an energy source, primarily C, is required by the microorganisms for the process to proceed. In humid climates such as those found in Atlantic Canada¹, denitrification is the predominant source of N_2O (Firestone and Davidson 1989; Granli and Bøckman 1994; Mosier 1998) and will be the primary focus of our

¹ Atlantic Canada experiences a cool humid Maritime climate with annual rainfall averaging between 900 and 2,000 mm annually, growing season temperatures averaging 8.5–12.5 °C, 170–180 frost free days and 2,000–2,700 crop heat units.

discussion here. Since denitrification is a respiratory process the primary factors that control denitrification relate to the supply of preferred terminal electron acceptor (O_2 availability or aeration), the demand for terminal electron acceptors (carbon availability) and the relative supply of alternate terminal electron acceptors, primarily NO_3^- availability. Other factors (e.g., temperature, pH, texture) also influence the denitrification process (Firestone and Davidson 1989; Granli and Bøckman 1994) but are less impacted by management practices in the potato production system.

14.2.1 Aeration

Denitrification commonly occurs at water-filled pore space (WFPS) of $0.70\text{ m}^3\text{ m}^{-3}$ and greater (Bateman and Baggs 2005). The rate of gaseous diffusion through the soil depends on water content and bulk density (Ball et al. 1999, 2008). Soils with greater bulk density have smaller pore volume. Similarly, greater soil water content reduces air-filled porosity. Both factors result in reduced and less continuous air-filled porosity, decreasing the rate of O_2 movement through the soil (Focht 1992). Increasing the percentage of WFPS has been shown to increase denitrification and N_2O emissions (Ruser et al. 1998, 2006; Ball et al. 1999, 2008; Flessa et al. 2002).

In C-rich environments, increased microbial activity can also result in reduced availability of O_2 . For example, Gillam et al. (2008) found that even in relatively well-aerated soils (WFPS $0.60\text{ m}^3\text{ m}^{-3}$), increased C availability can substantially increase N_2O emissions in soils through its influence on O_2 consumption. In comparison, N_2O emissions were negligible at WFPS below $0.45\text{ m}^3\text{ m}^{-3}$ due to enhanced aeration, or above $0.75\text{ m}^3\text{ m}^{-3}$ because restricted gaseous diffusion limits the diffusion of N_2O away from the site of denitrification thereby favoring the further reduction of N_2O to N_2 , and consequently C availability has a more limited effect on N_2O emissions under these conditions.

The WFPS varies in ridges and furrows. It is consistently greater in the furrow than in the ridge (Burton et al. 2008a; Dandie et al. 2008; Haile-Mariam et al. 2008). This difference is due in large part to differences in soil bulk density. For example, soil bulk density for 0–15 cm depth in the ridge and furrow were commonly 1.0 and 1.2 Mg m^{-3} , respectively, in the study of Burton et al. (2008a). Greater WFPS in the furrow can also reflect the redistribution of water after rainfall events, and the greater loss of water from the ridge due to transpiration (Zebarth and Milburn 2003). The greater total pore volume and preponderance of large pores in the ridge results in a soil in which the pores are largely filled with air. The presence of continuous air-filled porosity greatly enhances the movement of O_2 into the soil (Focht 1992). The enhanced supply of O_2 to the microbial community suppresses anaerobic processes such as denitrification (Robertson and Tiedje 1987; Focht 1992; Granli and Bøckman 1994). This is consistent with reports of increased N_2O emissions in furrows that were compacted as a result of wheel traffic (Ruser et al. 1998; Thomas et al. 2004) and with increased denitrification in furrows compared with ridges (Dandie et al. 2008).

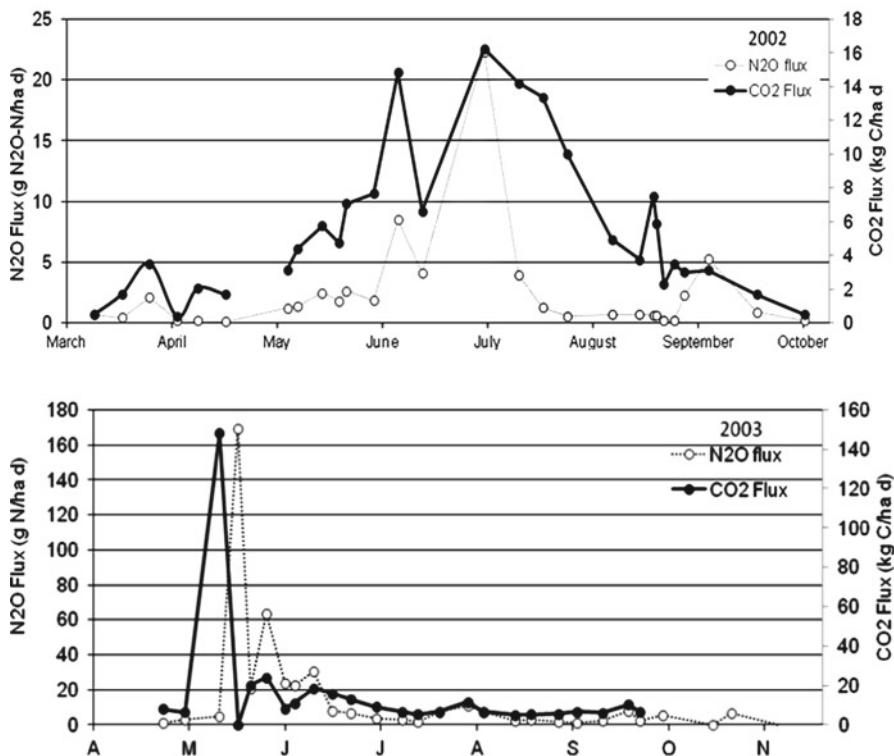


Fig. 14.2 Synchrony of nitrous oxide (open symbols; $\text{g N}_2\text{O-N ha}^{-1} \text{d}^{-1}$) and carbon dioxide (closed symbols; $\text{kg CO}_2\text{-C ha}^{-1} \text{d}^{-1}$) emissions in the 2002 and 2003 growing seasons from a potato crop in New Brunswick (Burton et al. 2008a)

14.2.2 Carbon Availability

Denitrification is a respiratory process where nitrogen oxides (NO_3^- , NO_2^- , NO and N_2O) are utilized as terminal electron acceptors by microorganisms in the absence of oxygen. Organic C substrates serve as a source of energy for heterotrophs in this process (Beauchamp et al. 1989). Carbon also has an indirect influence on denitrification by increasing the consumption of O_2 during aerobic respiration stimulating the formation of anoxic sites within the soil (Smith 1980; Hojberg et al. 1994). Sources of soil C inputs include soil organic matter, the potato rhizosphere, residues from the preceding crop, senescing leaves and roots from the current crop, and organic amendments added to the soil. In most cases soil management results in all of these sources being concentrated in the potato ridge, either as a result of ridge formation or as a result of the location of the potato plant. The greater concentration of the organic carbon in the potato ridge results in greater microbial activity in these locations and greater N_2O and CO_2 emissions (Fig. 14.2; Haile-Mariam et al. 2008).

Management and climatic conditions influence the quantity, quality and availability of organic carbon compounds. Management may directly influence carbon availability as a result of carbon addition (manure, compost or crop residues), altered quality of the organic substrates (Zebarth et al. 2009b, c) or the introduction of a plant (Sey et al. 2010). Management may also indirectly influence carbon availability as a result of soil disturbance such as tillage, which results in a flush of carbon metabolism (Alvarez et al. 2001), or as a result of plant desiccation with herbicide (Tenuta and Beauchamp 1996; Flessa et al. 2002). Climatic events such as the rewetting of dry soil following precipitation (Birch 1958) or the thawing of a frozen soil also result in a flush of microbial activity (Christensen and Tiedje 1990) and N_2O emissions (Burton and Beauchamp 1994).

Carbon availability is one of the primary controllers of N_2O emissions (Firestone and Davidson 1989; Granli and Bøckman 1994). The availability of C sources in the soil influences the magnitude of the denitrification process as well as the products of the denitrification process, specifically the N_2O molar ratio (i.e. $N_2O:N_2+N_2O$) (Baggs et al. 2000). Gillam et al. (2008) determined that N_2O emissions only increased with NO_3^- addition when C was also added; NO_3^- addition alone did not necessarily stimulate N_2O emissions. Increasing the availability of C substrates has been shown to increase (Dendooven et al. 1996) or decrease (Weier et al. 1993) the N_2O molar ratio. Miller et al. (2008) found that the relationship between the supply of, and demand for, terminal electron acceptors (TEAs), as determined by the relative availability of C and NO_3^- , influenced the amount of denitrification and the N_2O molar ratio for both simple (glucose) and complex C sources (plant residues).

The form of C also has a significant influence on denitrification and N_2O emissions. Gillam et al. (2008) found ground red clover was equivalent to glucose in its ability to stimulate N_2O emissions per unit of available C added, but the greater C:N ratio of barley straw resulted in less CO_2 and N_2O emissions (Gillam et al. 2008). Similarly, Miller et al. (2008) found that C from ground red clover was equivalent to glucose C in stimulating the microbial population. Furthermore, Miller et al. (2008, 2009) found N_2O emissions to be linearly related to C utilization by microbes as indicated by soil respiration across a wide range of carbon sources (glucose, plant residues, manures).

14.2.3 Nitrate Availability

Nitrate has been found to limit denitrification when NO_3^- concentrations are low ($< 5\text{--}10\text{ mg N kg}^{-1}$ soil; Ryden 1983), a situation not commonly found in soils cropped to potato. In agricultural soils where NO_3^- often accumulates to $> 10\text{ mg N kg}^{-1}$ soil, the availability of NO_3^- was found to have no effect on denitrification but a significant effect on the N_2O molar ratio (Gillam et al. 2008). The influence of NO_3^- on the N_2O molar ratio is due to NO_3^- being a more favorable electron acceptor than is N_2O (Betlach and Tiedje 1981; Cho et al. 1997), and therefore its presence in soil suppresses both the expression (Firestone et al. 1979) and activity (Betlach and Tiedje 1981)

of nitrous oxide reductase enzyme. The N_2O molar ratio is influenced by the relative availability of N-oxides and C, as simple or complex sources (Weier et al. 1993; Miller et al. 2008). Concentrations of NO_3^- -N ranging from 100 to 300 kg Nha^{-1} soil can inhibit N_2O reductase activity (Blackmer and Bremner 1978; Weier et al. 1993), reducing the conversion of N_2O to N_2 and thereby making N_2O the principle product of denitrification (Blackmer and Bremner 1978; Firestone et al. 1979; Weier et al. 1993).

In potato production systems in Atlantic Canada, Dandie et al. (2008) found that in the ridge, the magnitude of N_2O emissions was comparable with the denitrification rate suggesting that most gaseous emissions occurred as N_2O . In contrast in the furrow, the denitrification rate was greater than N_2O emissions, suggesting there was significant conversion of N_2O to N_2 . This was attributed to the N fertilizer being concentrated in the potato ridge as a result of banded fertilizer application, and the increased NO_3^- concentration decreasing N_2O reduction, increasing the N_2O molar ratio of denitrification.

14.2.4 Denitrifier Community

Denitrifiers are mainly aerobic heterotrophs (utilize C as an energy source) and are not necessarily controlled by the presence of anaerobic conditions or NO_3^- availability in the soil (Murray et al. 1990). Several microcosm studies using agricultural soils from potato production systems investigated the effect of organic C availability and source under completely anoxic conditions. Miller et al. (2008, 2009) found that C from plant residues or manures applied at 0–500 mg Ckg^{-1} soil did not increase the abundance of broad groups of denitrifiers but did increase denitrification rate and N_2O emissions. In contrast, the abundance of a broad group of denitrifiers, N_2O emissions and denitrification all increased in soil amended with plant residues at 1,000 mg Ckg^{-1} soil (Henderson et al. 2010). Plant residues with different C/N ratios increased similarly the abundance of a broad group of denitrifiers (Henderson et al. 2010). These findings suggest that abundance of broad groups of denitrifiers increase when availability of organic carbon is greater than 1000 mg Ckg^{-1} soil but that the source of organic carbon had little influence on growth.

Nitrate and reduced intermediate products induce denitrification gene expression under anoxic conditions (Saleh-Lakha et al. 2009). Denitrification gene expression in a smaller group of denitrifiers, *Pseudomonas mandelii* and related species (Dandie et al. 2007) increased with nitrate addition in soil without organic C amendment (Shannon et al. 2011). In contrast, there was no increase in denitrification gene expression in response to soil NO_3^- addition following organic amendment even despite there being an increase in denitrification rate (Shannon et al. 2011).

It is not clear whether the abundance of the denitrifier community and/or their denitrification gene expression play a role in controlling denitrification and N_2O emissions. Several studies found no relationship between abundance of denitrifiers (Dandie et al. 2007; Miller et al. 2008, 2009; Henderson et al. 2010; Shannon et al. 2011)

or denitrification gene expression (Henderson et al. 2010; Shannon et al. 2011) and N_2O emissions or denitrification rate. These findings suggest that the denitrification activity was decoupled from the abundance and denitrification gene expression of denitrifiers and that control over the magnitude of denitrification might be occurring primarily at the level of the denitrifying enzymes. Absence of relationships between abundance and gene expression could also be explained from the lack of information as to which denitrifier species are active in a particular environment and from limitations in the tools used to quantify the denitrifiers.

14.3 Temporal and Spatial Variation in N_2O Emissions

14.3.1 Temporal Variation

The interaction between the controlling factors discussed above result in highly episodic N_2O emissions. Despite this episodic nature, seasonal patterns in N_2O emissions are frequently observed. Following spring thaw and during the early part of the growing season soil moisture conditions, the release of organic carbon and the availability of NO_3^- often combine to result in large N_2O emissions (Christensen and Tiedje 1990). This has often been observed in potato production systems in Atlantic Canada (Fig. 14.2) but is not always the case. N_2O emissions are, however, seldom monitored during the non-cropping period (November to May). In studies that have examined the non-cropping period in temperate climates, the emissions can be significant in the autumn and spring periods (Wagner-Riddle and Thurtell 1998; Ruser et al. 2006). This may be particularly true in the autumn to spring period following potato production where residual NO_3^- after harvest is large (Zebarth et al. 2003).

The location, timing and intensity of C availability combine to determine the magnitude of N_2O emissions (Ball et al. 2008). This can be seen in the similarity in patterns of N_2O and CO_2 emissions (Fig. 14.2). The spring flush of CO_2 and N_2O emissions is often attributed to the release of C following soil thawing (Christensen and Tiedje 1990; Burton and Beauchamp 1994) or as a result of tillage operations (Alvarez et al. 2001). The rewetting of dry soil can also result in a flush of respiration and has been shown to result in N_2O emission events (Zebarth et al. 2008a). Snowden (2010) demonstrated that the preceding crop significantly affected denitrification and N_2O emissions from the potato crop. While there were no significant differences in N_2O or CO_2 emissions during the growth of the non-potato rotational crops, the subsequent potato crop had greater rates of denitrification and N_2O emissions where the preceding crops were forages (red clover, Italian ryegrass). This effect was attributed to the quality of the forage crop as a substrate driving denitrification. Nitrate exposure (a temporally integrated measure of NO_3^- concentration), CO_2 emissions and WFPS were able to explain 60% of the variation in cumulative growing season N_2O emissions from the potato crop (Snowden 2010).

14.3.2 Spatial Variations in N_2O Emissions and Denitrification

The spatial distribution of water is one the primary factors that govern where denitrification and N_2O emissions occur. The movement of water falling on the soil as precipitation through the soil profile and along landscape features results both in the transport of C and N compounds, particularly NO_3^- , as well as influencing the water content and therefore aeration status of the soil environment. Consideration of the influence of hydrology on the spatial distribution of N_2O emissions must be addressed at several scales: the ridge-furrow complex, the soil profile, and the landscape.

14.3.2.1 Ridge-Furrow Complex

Water is not uniformly distributed in the potato ridge-furrow complex. Water applied to a potato field, whether as rainfall or irrigation, tends to accumulate in the furrow due to runoff from the ridge and leaf-drip from the outer foliage system (Saffigna et al. 1976). There is also greater soil wetting at the base of the plant due to stemflow. Zebarth and Milburn (2003) reported lower soil water content in the ridge than in the furrow in a potato field, a finding attributed to greater loss of water from the ridge by transpiration because no difference in water content was measured when no plants were present.

The architecture of the potato ridge-furrow complex is important in influencing both denitrification and N_2O emissions. The furrow locations systematically maintain a greater percentage of water-filled pores than do ridges (Table 14.1). The greater WFPS results in the impeded diffusion of O_2 into the soil, favoring denitrification (Table 14.1), and impeded diffusion of N_2O away for the site of denitrification, resulting in a lower N_2O molar ratio. The lower N_2O molar ratio is also favored by the low NO_3^- concentration in the furrow because fertilizer N is banded in the ridge. By comparison, the ridge has lower WFPS due to lower soil water content and soil bulk density, and consequently is less favorable for denitrification (Table 14.1). Despite the greater potential of gas exchange, denitrification does occur in the ridge due to the presence of organic matter rich soil and the potato rhizosphere resulting in a large rate of O_2 consumption. In addition, the presence of large concentrations of NO_3^- in the ridge ensure that when O_2 supply cannot meet demand, denitrification will result in N_2O being the primary end product and the subsequent reduction of N_2O to N_2 will be limited due to the greater substrate affinity of the nitrate reductase compared to the N_2O reductase (Betlach and Tiedje 1981).

The end result of this architecture and the placement of N fertilizer in the ridge is that the potato ridge has a lower rate of denitrification, but greater N_2O emissions, compared with the furrow (Table 14.1; Burton et al. 2008a; Dandie et al. 2008). Where fertilizer N is broadcast, resulting uniform distribution of NO_3^- , greater N_2O emissions occur from the furrow, particularly compacted furrows, and over-all N_2O emissions from the field are greater (Ruser et al. 1998).

Table 14.1 Influence of row location (ridge, furrow) on cumulative growing season N₂O emissions, cumulative CO₂ emissions, mean denitrification rate and mean water-filled pore space (WFPS) as influenced fertilizer N management (N0=0 N; N200=200 kg N ha⁻¹ at planting; N120+80=120 kg N ha⁻¹ at planting plus 80 kg N ha⁻¹ at final ridge formation in a potato crop located in New Brunswick (Burton et al. 2008a)

Treatment	2002		2003	
	Ridge	Furrow	Ridge	Furrow
Cumulative N ₂ O emissions	(kg N ha ⁻¹)			
N0	0.19	0.19	0.64	0.62
N200	0.98	0.32	3.09	1.32
N120+80	0.59	0.32	2.15	0.94
SEM (n=4, df=8)				0.35
Cumulative CO ₂ emissions	(Mg C ha ⁻¹)			
N0	1.18	1.01	1.16	1.12
N200	1.38	0.89	1.09	0.87
N120+80	1.16	0.80	1.31	0.92
SEM (n=4, df=8)				0.27
Mean denitrification	(kg N ha ⁻¹)			
N0	1.7	6.5	2.8	41
N200	15.1	22.2	45.2	24.3
SEM (n=4, df=12)				10.5
Mean WFPS	(m ³ m ⁻³)			
N0	0.39	0.64	0.35	0.52
N200	0.40	0.65	0.38	0.59
SEM (n=4, df=12)				0.02

SEM standard error of the mean

The distinct soil environments within the ridge-furrow complex also result in distinguishable changes in the abundance and diversity of the soil denitrifier community. Distinct differences in denitrifier community abundance (Dandie et al. 2008) and diversity (Wertz et al. 2009) were measured between the ridge and furrow, and also between locations within the ridge that were adjacent to or more distal from the plant. However the spatial distribution of the denitrifier communities within the ridge-furrow complex did not match the spatial distribution of denitrification activity. Thus, as indicated above, denitrifier abundance is de-coupled from denitrification activity. This shows that soil environmental conditions influence the activity of denitrifier enzymes and that greater denitrification is not necessarily the result of greater gene abundance (Dandie et al. 2008; Wertz et al. 2009).

14.3.2.2 Soil Profile

The ridge-furrow complex is hydrologically connected to the underlying soil as a result of the water draining through the soil profile. While the most biologically active region of the soil occurs at the soil surface, microbial processes also occur in the sub-surface. Water not only influences the potential for denitrification through its impacts on aeration, but also as the primary means by which C and NO₃⁻ are

Fig. 14.3 Influence of N source on the N_2O concentration of the soil profile of a potato–barley–red clover rotation. Sampling was done in the spring prior to the potato phase of the rotation following fall manure application but prior to spring manure applications

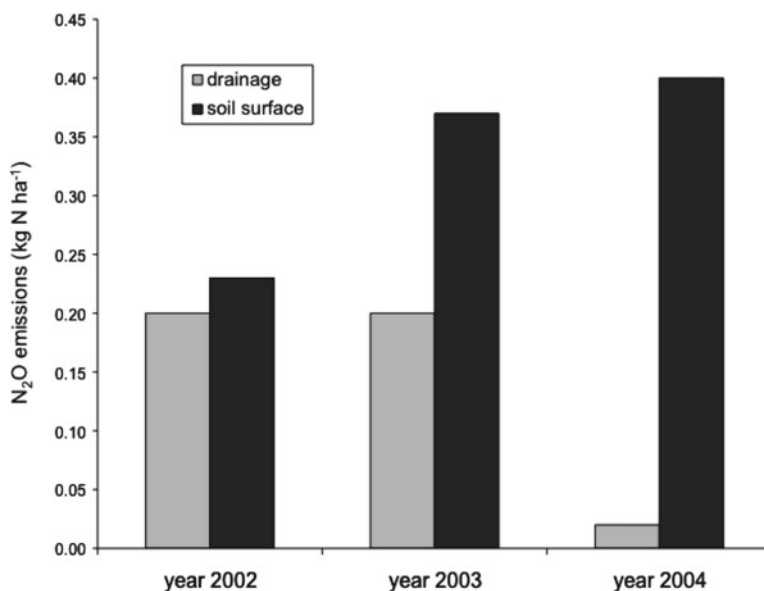
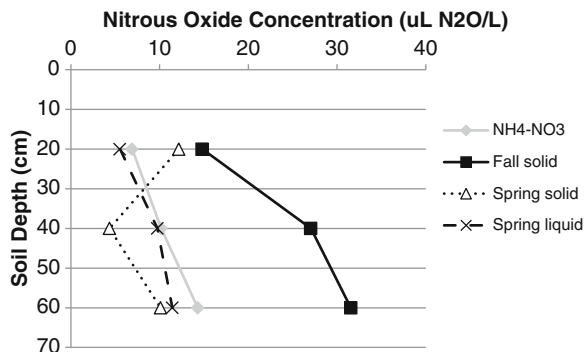


Fig. 14.4 Annual emissions of N_2O dissolved in tile drainage water (drainage) or emitted from the soil surface (soil surface) in a soil cropped to barley (2002), red clover (2003), and in the spring period following red clover plow-down (2004)

delivered to the sub-surface. Examination of the N_2O concentration in the soil profile of a potato – barley – red clover rotation revealed that the greatest concentrations of N_2O were often not found in the biologically active surface layer but at depth (Fig. 14.3). Fall application of solid swine manure resulted in an increase in N_2O concentration throughout the profile and in particular at 60 cm depth. This result points to the role of leaching of C and N, even if applied at the soil surface, in influencing the magnitude and location of N_2O production (Burton and Beauchamp 1994) and denitrification (Paul et al. 1997).

In Atlantic Canada many potato producers have installed tile drainage as a means of removing excess water from their fields during the spring period. Examination of N_2O emitted in tile drainage water indicated that dissolved N_2O emissions could be

as great in some years as those coming from the soil surface (Fig. 14.4; Burton et al. 2008b). The relative importance of surface emissions relative to dissolved N_2O was a function of preceding crop and precipitation. In 2002, the year following potato production, large quantities of residual NO_3^- and a wet autumn combined to favor the production of N_2O in the sub-surface and its loss in tile-drainage water (Fig. 14.4). Lower soil NO_3^- accumulation and reduced precipitation in the barley and red clover phases of the rotation resulted in lower dissolved N_2O emissions.

14.3.2.3 Landscape

The influence of water on the distribution of denitrification and its end products extends beyond the soil profile. In soil landscapes, lower positions in the landscape have greater water contents for longer periods of time. This has the potential to result in greater denitrification and N_2O emissions. The degree to which this potential is realized is a function of the architecture of the system. As an example, consider the N_2O emissions from a soil landscape located in a single field in New Brunswick where soils vary primarily in terms of internal drainage (Fig. 14.5). In this landscape, a catena of soils exist along the slope with the Research Station Association being located in the uppermost slope positions and the Fundy Association being located at the lowest positions. In 2002, a large precipitation event in July resulted in a period of very large N_2O emissions and these were greatest in the lower slope positions. The remainder of the year had little to no N_2O emissions and there was no difference among slope positions. Similar patterns were seen in the rate of denitrification with greatest denitrification occurring on the July sampling date and at the lower slope position (Fig. 14.6). In contrast, lower precipitation and the lack of a large growing season rainfall event in 2003 resulted in lower rates of N_2O emissions and no clear pattern in N_2O emissions (Fig. 14.5) or denitrification (Fig. 14.6) with slope position. This emphasizes the situational nature of the controls of the denitrification process and its products.

14.4 Implications of Management on N_2O Emissions

14.4.1 Crop Species

One of the most profound influences on soil biology and its activity is the choice of crop species grown. Crop species differ in the nature and extent of the plant root system and its associated rhizosphere, fertility requirements, residue quality (C/N ratio, lignin content), and soil and water management practices. These conditions also influence the potential for N_2O emissions. Potato is often grown in rotation with other crops, often in 2- or 3-year rotations. The potential for N_2O production during the non-potato phases should also be considered in the overall N_2O emission profile of the potato production system and may offer an opportunity to reduce the N_2O emissions from this production system. Snowden (2010) demonstrated that the preceding crop has an impact on the N_2O emissions occurring during potato

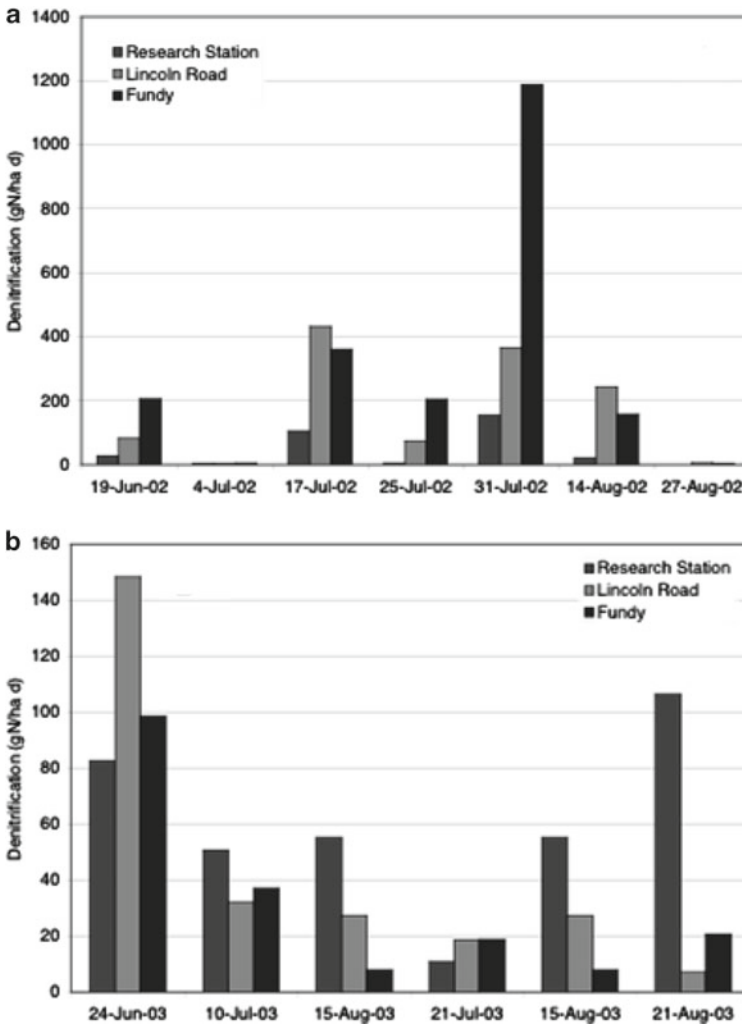


Fig. 14.6 Denitrification rate measured using the acetylene blockage method as influenced by soil association in a landscape study under potato production in New Brunswick: (a) 2002, (b) 2003

growth and attributed this to differences in the C/N ratio and quantity of crop residue returned and the subsequent impacts on C and NO_3^- availability. An examination of the N_2O emissions associated with each phase of a potato–barley–red clover rotation indicated that N_2O emissions were generally related to the accumulation of NO_3^- in the soil (Fig. 14.7; Burton 2005). Nitrate exposure, an integrated measure of NO_3^- concentration over time, explained 65% of the variation in cumulative growing season N_2O emissions across the three cropping seasons (Fig. 14.7). Periods of large emissions were generally associated with periods of NO_3^- accumulation as a result of N fertilization or the plow-down of N-rich red clover residues. One exception to

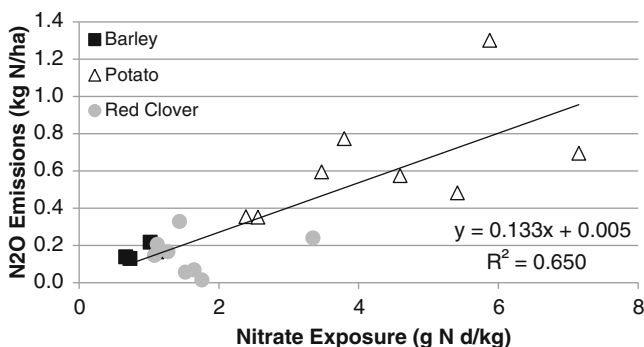


Fig. 14.7 Relationship between nitrate exposure and cumulative growing season N_2O emissions as measured in a potato-barley-red clover crop rotation located at the Crops and Livestock Research Station, Charlottetown, PE (Burton 2005)

this generalization was large N_2O emissions in the spring of the red clover phase that was attributed to precipitation events. Selection of rotational crops that maintain small soil NO_3^- concentrations through plant uptake or smaller rates of N application will generally result in smaller N_2O emissions. For potatoes grown in 2-year rotations, differences in cumulative N_2O emissions during the potato phase could be explained primarily by the effect of the preceding crop on soil nitrate availability (measured as nitrate exposure). The exception was where the preceding crop was a legume or non-legume forage crop, where N_2O emissions were greater than would be expected based on nitrate exposure alone, a finding attributed to increased N_2O emissions early in the growing season due to enhanced respiration (Snowden 2010).

14.4.2 Fertilizer N Management

Emissions of N_2O can be influenced by the rate, timing, placement and form of fertilizer N applied. In general, N_2O emissions increase as a function of N application rate, and this has also been reported for potato production (Ruser et al. 2001). This concept forms the basis of the IPCC coefficient for N_2O emissions associated with fertilizer application that assumes that 1% of the applied N fertilizer is emitted as N_2O on an annual basis (IPCC 2007).

While research is limited on the effect of fertilizer N rate on N_2O emissions in potato production in Atlantic Canada, greater N_2O emissions were measured for potatoes grown with 200 kg N ha^{-1} applied than with an unfertilized control due to increased soil NO_3^- concentration (Burton et al. 2008a). This concept is also demonstrated in the relationship between nitrate exposure and cumulative growing season N_2O emissions (Fig. 14.7). Nitrate exposure increases with increasing N rate (Burton et al. 2008a; Zebarth et al. 2008a) and also results in increased N_2O

emissions. In other crop species, N_2O emissions increased with increasing fertilizer N rate on barley in New Brunswick, and the increase in emissions per unit of N applied was greater for N rates above the optimal application rate (Zebarth et al. 2008a). However, fertilizer N application does not necessarily increase N_2O emissions in all cases. Application of additional N pre-plant or at sidedress to corn in New Brunswick did not significantly increase N_2O emissions compared with a treatment that received starter fertilizer N only (Zebarth et al. 2008b).

Emissions of N_2O are highly sporadic and event driven. It seems reasonable to expect management practices that avoid the accumulation of NO_3^- , in the presence of available organic C under restricted aeration, will result in reduced N_2O emissions. The timing of N fertilizer application is one such example. Split application of NH_4NO_3 has been shown to result in reduced N_2O emissions (Burton et al. 2008a), but this only occurred in a year when there was significant precipitation between the initial application of N fertilizer and the split application. Thus, while split application of N fertilizer has the potential to reduce N_2O emissions and increase N use efficiency, this practice will only do so in the years where the conditions are favorable for N losses during the timing between planting and the split application of N.

The placement of N fertilizer in the potato ridge is a common practice in Atlantic Canada. Earlier in this chapter we described why this results in an increase in the N_2O molar ratio, resulting in more N_2O emissions from the ridge than if no NO_3^- was present. Other studies have shown that the broadcast of N fertilizer results in an increase in the N_2O molar ratio in both ridge and furrow (Ruser et al. 1998). Placement of the N fertilizer in the potato ridge lowers the soil NO_3^- concentration in the furrow, the area of most active denitrifying activity (Table 14.1; Burton et al. 2008a) and therefore results in lower overall N_2O emissions.

Controlled release N fertilizer products have been shown to increase nitrogen-use efficiency (Shoji et al. 2001) and reduce N_2O emissions (Hyatt et al. 2010). Plant N uptake can be greater with controlled release N fertilizer products than conventional products, particularly on sandy soils (Shoji et al. 2001; Wilson et al. 2009; Ziadi et al. 2011). Hyatt et al. (2010) reported reduced N_2O emissions with application of a polymer-coated urea product compared with conventional fertilizer N products in irrigated potato production on sandy soils in Minnesota. Controlled-release products are most likely to be most beneficial in reducing N_2O emissions when the rates of application are reduced to reflect the increased efficiency of delivery of the controlled release product.

14.4.3 Influence of Tile Drainage

Tile-drainage influences N_2O emissions in several ways. The most obvious is by reducing the extent and duration of water accumulation within the soil profile. Greater water accumulation increases the potential for anoxic processes such as denitrification, potentially resulting in greater N_2O production. Alternatively, greater water accumulation may also result in a reduced N_2O molar ratio under very wet

conditions, potentially reducing N_2O emissions. As a result, the introduction of tile drainage may increase or decrease N_2O emissions. The relative importance of these two opposing influences will vary from year-to-year and from site-to-site.

The less obvious implication of tile drainage is its role in transporting NO_3^- and dissolved organic carbon into the soil subsurface and for the production of N_2O and its loss as dissolved N_2O in tile drainage water. As indicated earlier (Fig. 14.4) the loss of N_2O dissolved in tile drainage water could be similar to, or much less than, surface emissions depending on management practices and climatic conditions.

14.4.4 Application of Manure

Animal manures and other organic nutrient sources are increasingly applied as nutrient amendments in potato rotations and as a means of increasing soil organic matter content. These amendments have the potential to increase denitrification and/or N_2O emissions as a result of both increased N and C availability. A study of the form of manure (solid vs. liquid) and the timing of manure application prior to potato production (autumn vs. spring), applied at equivalent rates, demonstrated that neither form of manure nor timing of application influenced N_2O emissions compared with NH_4NO_3 as an N source (Table 14.2). Greater differences were observed between the various phases of the crop rotation (i.e., crop species) than the manure application

14.5 Conclusions

The basic biology of the denitrification process is well understood and the environmental factors that control denitrification have been well studied under controlled conditions. The supply of electron acceptors (O_2 , NO_3^-) in combination with the demand for electron acceptors (C availability) determines the extent of denitrification and N_2O molar ratio of the products of denitrification. In the potato production system the formation of a potato ridge results in two distinct environments – a more aerobic ridge and a less aerobic furrow. In Atlantic Canada the banding of fertilizer in the ridge results in increased N_2O emissions from the ridge but reduced emissions from the furrow resulting in lower overall emissions. As a result the N_2O emissions from potato production in Atlantic Canada during the growing season are relatively modest, frequently less than the assumed value for annual emissions of 1% of applied fertilizer N application used by the IPCC (2007). Furthermore, the split application of N fertilizer has the potential to reduce N_2O emissions in years when there is rainfall in the early part of the growing season. The potential for N_2O loss during the non-growing season and/or the loss of N_2O in tile drainage water has yet to be adequately assessed. Annual N_2O emissions are usually related to N application rate but are also influenced by other management factors such as the timing of

Table 14.2 Cumulative N₂O emissions as influenced by location (ridge vs. furrow), nitrogen source and timing of application in (a) 2001-potato; (b) 2002-barley under-seeded to red clover; (c) 2003-red clover; and (d) Spring 2004 (following fall manure application and plow-down of red clover). Note that manure was applied in the fall 2000/spring 2001 and again in fall 2003/spring 2004 (Burton et al. 2005)

(a) Potato 2001			
Nitrogen source	Location	Gross emissions (kg N ha ⁻¹)	Field estimates (kg N ha ⁻¹)
Solid manure (Fall)	Hill	0.42	0.46
	Furrow	0.50	
Solid manure (Spring)	Hill	0.42	0.42
	Furrow	0.41	
Liquid manure (Spring)	Hill	0.71	0.61
	Furrow	0.51	
Inorganic fertilizer (Spring)	Hill	0.71	0.61
	Furrow	0.51	
(b) Barley 2002			
Nitrogen source			Field estimates (kg N ha ⁻¹)
Solid manure (Fall)			0.13
Solid manure (Spring)			0.15
Liquid manure (Spring)			0.20
Inorganic fertilizer (Spring)			0.12
(c) Red Clover 2003			
Nitrogen source			Field estimates (kg N ha ⁻¹)
Solid manure (Fall)			0.77
Solid manure (Spring)			0.57
Liquid manure (Spring)			0.49
Inorganic fertilizer (Spring)			0.52
(d) Spring 2004 (following plow down)			
Nitrogen source			Field estimates (kg N ha ⁻¹)
Solid manure (Fall)			0.74
Solid manure (Spring)			0.66
Liquid manure (Spring)			0.75
Inorganic fertilizer (Spring)			0.40

N fertilizer application, manure application and the preceding crop. In general, management practices that reduce the accumulation of NO₃⁻ in the soil will likely result in reduced N₂O emissions. This underscores the need for better tools to manage nitrogen in potato production (Chaps. 13 and 14) and effective monitoring tools (nitrate exposure).

References

- Alvarez R, Alvarez DR, Lorenzo G (2001) Carbon dioxide fluxes following tillage from a mollisol in the Argentine rolling pampa. *Eur J Soil Biol* 37:161–166
- Baggs E, Rees R, Smith K, Vinten A (2000) Nitrous oxide emission from soils after incorporating crop residues. *Soil Use Manage* 16:82–87

- Ball B, Scott A, Parker J (1999) Field N_2O , CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. *Soil Tillage Res* 53:29–39
- Ball B, Crichton I, Horgan G (2008) Dynamics of upward and downward N_2O and CO_2 fluxes in ploughed or no-tilled soils in relation to water-filled pore space, compaction and crop presence. *Soil Tillage Res* 101:20–30
- Bateman E, Baggs E (2005) Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. *Biol Fertil Soils* 41:379–388
- Beauchamp EG, Trevors JT, Paul JW (1989) Carbon sources for bacterial denitrification. *Adv Soil Sci* 10:113–142
- Betlach MR, Tiedje JM (1981) Kinetic explanation for accumulation of nitrite, nitric oxide, and nitrous oxide during bacterial denitrification. *Appl Environ Microbiol* 42:1074–1084
- Birch HF (1958) The effect of soil drying on humus decomposition and nitrogen availability. *Plant Soil* 10:9–31
- Blackmer AM, Bremner JM (1978) Inhibitory effect of nitrate on reduction of N_2O to N_2 by soil microorganisms. *Soil Biol Biochem* 10:187–191
- Burton DL (2005) Best management practices for the reduction of greenhouse gas emissions. Final report to Climate Change Funding Initiative in Agriculture, Agriculture and Agri-Food Canada
- Burton DL, Beauchamp EG (1994) Profile nitrous oxide and carbon dioxide concentrations in a soil subject to freezing. *Soil Sci Soc Am J* 58:115–122
- Burton DL, Zebarth BJ, Gillam KM, MacLeod JA (2008a) Effect of split application of fertilizer nitrogen on N_2O emissions from potato. *Can J Soil Sci* 88:229–239
- Burton DL, Thangaraj B, Gordon R (2008b) Nitrous oxide emissions and tile drain water quality during spring thaw. Nova Scotia Technology Development Program Final Report. Project DEV21-094
- Cho CM, Burton DL, Chang C (1997) Denitrification and fluxes of nitrogenous gases from soil under steady state oxygen distribution. *Can J Soil Sci* 77:261–269
- Christensen S, Tiedje JM (1990) Brief and vigorous N_2O production by soil at spring thaw. *J Soil Sci* 41:1–4
- Crutzen PJ, Ehhalt DH (1977) Effects of nitrogen fertilizers and combustion on the stratospheric ozone layer. *Ambio* 6:112–117
- Dandie CE, Miller MN, Burton DL, Zebarth BJ, Trevors JT, Goyer C (2007) Nitric-oxide reductase-targeted real-time PCR quantification of denitrifier populations in soil. *Appl Environ Microbiol* 73:4250–4258
- Dandie CE, Burton DL, Zebarth BJ, Henderson SL, Trevors JT, Goyer C (2008) Changes in bacterial denitrifier community abundance over time in an agricultural field and their relationship with denitrification activity. *Appl Environ Microbiol* 74:5997–6005
- Dendooven L, Splatt P, Anderson J (1996) Denitrification in permanent pasture soil as affected by different forms of C substrate. *Soil Biol Biochem* 28:141–149
- Environment Canada (2010) National Inventory Report 1990–2008: greenhouse gas sources and sinks in Canada. ISBN 978-1-100-15579-1. <http://www.ec.gc.ca/ges-ghg>. Accessed 2 May 2011
- Firestone MK, Davidson EA (1989) Microbiological basis of NO and N_2O production and consumption in soil. In: Andreae MO, Schimel DS (eds) Exchange of trace gases between terrestrial ecosystems and the atmosphere. John Wiley and Sons, New York
- Firestone MK, Smith MS, Firestone RB, Tiedje JM (1979) The influence of nitrate, nitrite, and oxygen on the composition of the gaseous products of denitrification in soil. *Soil Sci Soc Am J* 43:1140–1144
- Flessa H, Ruser R, Schilling R, Loftfield N, Munch J, Kaiser E, Beese F (2002) N_2O and CH_4 fluxes in potato fields: automated measurement, management effects and temporal variation. *Geoderma* 105:307–325
- Focht DD (1992) Diffusional constraints on microbial processes in soil. *Soil Sci* 154:300–307
- Gillam KM, Zebarth BJ, Burton DL (2008) Nitrous oxide emissions from denitrification and the partitioning of gaseous loss as affected by nitrate and carbon addition and soil aeration. *Can J Soil Sci* 88:133–143

- Granli T, Bøckman OC (1994) Nitrous oxide from agriculture. *Norw J Agric Sci Suppl* 12:128pp
- Haile-Mariam S, Collins HP, Higgins SS (2008) Greenhouse gas fluxes from an irrigated sweet corn (*Zea mays* L.) – potato (*Solanum tuberosum* L.) rotation. *J Environ Qual* 37:759–771
- Henderson SL, Dandie CE, Patten CL, Zebarth BJ, Burton DL, Trevors JT, Goyer C (2010) Changes in denitrifier abundance, denitrification gene mRNA levels, nitrous oxide emissions, and denitrification in anoxic soil microcosms amended with glucose and plant residues. *Appl Environ Microbiol* 76:2155–2164
- Højberg O, Revsbech NP, Tiedje JM (1994) Denitrification in soil aggregates analyzed with microensors for nitrous oxide and oxygen. *Soil Sci Soc Am J* 58:1691–1698
- Hyatt CR, Venterea RT, Roen CJ, McNearney M, Wilson ML, Dolan MS (2010) Polymer-coated urea maintains potato yields and reduces nitrous oxide emissions in a Minnesota loamy sand. *Soil Sci Soc Am J* 74:419–428
- IPCC (2007) *Climate Change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds)). Cambridge University Press, Cambridge, United Kingdom and New York
- Matson PA, Parton WJ, Power AG, Swift MJ (1997) Agricultural intensification and ecosystem properties. *Science* 277:504–509
- Miller MN, Zebarth BJ, Dandie CE, Burton DL, Goyer C, Trevors JT (2008) Crop residue influence on denitrification, N₂O emissions and denitrifier community abundance in soil. *Soil Biol Biochem* 40:2553–2562
- Miller MN, Zebarth BJ, Dandie CE, Burton DL, Goyer C, Trevors JT (2009) Influence of liquid manure on soil denitrifier abundance, denitrification, and nitrous oxide emissions. *Soil Soc Am J* 73:760–768
- Mosier A (1998) Soil processes and global change. *Biol Fert Soils* 27:221–229
- Murray RE, Parsons LL, Smith MS (1990) Aerobic and anaerobic growth of rifampin-resistant denitrifying bacteria in soil. *Appl Environ Microbiol* 56:323–328
- Paul JW, Etches V, Zebarth BJ (1997) Increased denitrification below the root zone in the fall following a spring manure application. *Can J Soil Sci* 77:249–251
- Robertson GP, Tiedje JM (1987) Nitrous oxide sources in aerobic soils: nitrification, denitrification and other biological processes. *Soil Biol Biochem* 19:187–193
- Ruser R, Flessa H, Schilling R, Steindl H, Beese F (1998) Effects of soil compaction and fertilization on N₂O and CH₄ fluxes in potato fields. *Soil Sci Soc Am J* 62:1587–1598
- Ruser R, Flessa H, Schilling R, Beese F, Munch JC (2001) Effect of crop-specific field management and N fertilization on N₂O emissions from a fine-loamy soil. *Nutr Cycl Agroecosyst* 59:177–191
- Ruser R, Flessa H, Russow R, Schmidt G, Buegger F, Munch JC (2006) Emission of N₂O, N₂ and CO₂ from soil fertilized with nitrate: effect of compaction, soil moisture and rewetting. *Soil Biol Biochem* 28:263–274
- Ryden JC (1983) Denitrification loss from a grassland soil in the field receiving different rates of nitrogen as ammonium nitrate. *J Soil Sci* 34:355–365
- Saffigna PG, Tanner CB, Keeney DR (1976) Non-uniform infiltration under potato canopies caused by interception, stemflow and hilling. *Agron J* 68:337–342
- Saleh-Lakha S, Shannon KE, Henderson SL, Goyer C, Trevors JT, Zebarth BJ, Burton DL (2009) Effect of nitrate and acetylene on *nirS*, *cnorB* and *nosZ* expression and denitrification activity in *Pseudomonas mandelii*. *Appl Environ Microbiol* 75:5082–5087
- Sey BK, Manceur AM, Whalen JK, Gregorich EG, Rochette P (2010) Root-derived respiration and nitrous oxide production as affected by crop phenology and nitrogen fertilization. *Plant Soil* 326:369–379
- Shannon KEM, Saleh-Lakha S, Burton DL, Zebarth BJ, Goyer C, Trevors JT (2011) Response of denitrification and nitric oxide reductase (*cnorB*) gene abundance and mRNA levels to additions of nitrate and glucose in anoxic soil microcosms. *Antonie van Leeuwenhoek J Microbiol* 100:183–195
- Shoji S, Delgado J, Mosier A, Miura Y (2001) Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. *Commun Soil Sci Plant Anal* 32:1051–1070

- Smith KA (1980) A model of the extent of anaerobic zones in aggregated soils, and its potential application to estimates of denitrification. *J Soil Sci* 31:263–277
- Snowden E (2010) Effects of soil nitrate and carbon availability and soil aeration on nitrous oxide emissions in two-year potato rotations. M.Sc. Thesis, Nova Scotia Agricultural College, Truro, NS, Canada, 89pp
- Tenuta M, Beauchamp E (1996) Denitrification following herbicide application to a grass sward. *Can J Soil Sci* 76:15–22
- Thomas S, Barlow H, Francis G, Hedderley D (2004) Emission of nitrous oxide from fertilised potatoes. In: Proceedings of the Australia New Zealand SuperSoil 2004 Conference, Sydney, Australia, 6–9 December 2004. <http://www.regional.org.au/au/asssi>
- Tillman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. *Nature* 418:671–677
- Wagner-Riddle C, Thurtell GW (1998) Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. *Nutr Cycl Agroecosyst* 52:151–163
- Weier K, Doran J, Power J, Walters D (1993) Denitrification and the dinitrogen to nitrous oxide ratio as affected by soil water, available carbon and nitrate. *Soil Sci Soc Am J* 57:66–72
- Wertz S, Dandie CE, Goyer C, Trevors JT, Patten CL (2009) Diversity of *nirK* denitrifying genes and transcripts in an agricultural soil. *Appl Environ Microbiol* 75:7365–7377
- Wilson ML, Rosen CJ, Moncrief JF (2009) Potato response to polymer-coated urea on an irrigated coarse-textured soil. *Agron J* 101:897–905
- Zebarth BJ, Milburn PH (2003) Spatial and temporal distribution of soil inorganic nitrogen concentration in potato hills. *Can J Soil Sci* 83:183–195
- Zebarth BJ, Rosen CJ (2007) Research perspective on nitrogen BMP development for potato. *Am J Potato Res* 84:3–18
- Zebarth BJ, Leclerc Y, Moreau G, Gareau R, Milburn PH (2003) Soil inorganic nitrogen content in commercial potato fields in New Brunswick. *Can J Soil Sci* 83:425–429
- Zebarth BJ, Rochette P, Burton DL (2008a) Growing season N₂O emissions from spring barley production as influenced by fertilizer nitrogen rate. *Can J Soil Sci* 88:197–205
- Zebarth BJ, Rochette P, Burton DL, Price M (2008b) Effect of fertilizer nitrogen management on N₂O emissions in commercial corn fields. *Can J Soil Sci* 88:189–195
- Zebarth BJ, Drury CF, Tremblay N, Cambouris AN (2009a) Opportunities for improved fertilizer nitrogen management in production of arable crops in eastern Canada: a review. *Can J Soil Sci* 89:113–132
- Zebarth BJ, Scott P, Sharifi M (2009b) Effect of straw and fertilizer nitrogen management for spring barley on soil nitrogen supply to a subsequent potato crop. *Am J Potato Res* 86:209–217
- Zebarth BJ, Arsenaault WJ, Moorehead S, Kunelius HT, Sharifi M (2009c) Italian ryegrass management effects on nitrogen supply to a subsequent potato crop. *Agron J* 101:1573–1580
- Ziadi N, Grant C, Samson N, Nyiraneza J, Bélanger G, Parent L-É (2011) Efficiency of controlled-release urea for a potato production system in Quebec, Canada. *Agron J* 103:60–66