The effect of crop rotation and soil amendments on soil N bioavailability and N_2O emissions

E. Snowdon[1], D. Lynch[2] and J. Schoenau[3]

[1]Western Ag Innovations, 3-411 Downey Road, Saskatoon, SK, S7J 4J6, [2]Organic Agriculture Centre of Canada, Nova Scotia Agricultural College, PO Box 550, Truro, NS, B2N 5E3, [3]University of Saskatchewan, Department of Soil Science, Saskatoon SK S7N 5A8

Key Words: nitrous oxide, crop rotation, crop residue, soil amendments, N bioavailability, denitrification

Abstract

The majority of N_2O emissions result from bacterial denitrification and to a lesser extent nitrification, occurring in agricultural soils. Therefore, the overall N economy of a system, along with soluble C and limited O_2 are the key drivers in the release of N_2O. Crop rotations and soil amendments readily add to or deplete the soil N economy depending on the C:N ratio of the biomass returned to the field. This paper synthesizes the results of three varied studies to further elucidate the role of management on key drivers of N_2O release. Study one examined how N_2O emissions during potato production are influenced by choice of preceding crop in two-year potato rotations. There was a significant effect of preceding crop (PC) on cumulative growing season N_2O emissions from the potato crop. Preceding crops of red clover and Italian ryegrass (average of 1.7 kg N_2O-N ha^{-1}) produced significantly higher cumulative N_2O emissions when compared to preceding crops of corn, canola, soybean, barley and potato (average of 0.8 kg N_2O-N ha^{-1}). A second study on potatoes conducted by Lynch et al. (2009) using Plant Root Simulator (PRS)™-probes found that a PC containing red clover increased soil N supply rates compared to a PC containing pea-oat-vetch. This increase in PRS™–N supply rates was associated with increased N_2O emission during the five-year potato rotation. The use of by-products from biofuel processing as soil amendments and N_2O emissions during canola production was assessed by Schoenau et al. (2009). Wet distillers' grain and thin stillage resulted in the greatest N_2O production compared with soil amendments of alfalfa powder and glycerol. PRS™–N supply rates were closely linked with these patterns of N_2O emissions. These results suggest that selection of rotation crops and soil amendments can have significant effects on N_2O emissions as affected by soil N bioavailability.

Introduction

Global climate change is an issue of increasing importance in recent years. Anthropogenic greenhouse gases (GHG) have substantially increased since pre-industrial times. For example, global anthropogenic GHG emissions have increased by 70% from 1970 to 2004 (Rogner et al. 2007). The most common GHGs resulting from human activities are carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), ozone (O_3) and halocarbons (Intergovernmental Panel on

Climate Change (IPCC) 2007). Because of the ample evidence linking climate change to anthropogenic GHG emissions (IPCC 2007), an understanding of the controls on these emissions is critical to development of effective mitigation strategies.

Nitrous oxide is an important GHG because it has a global warming potential 296 times greater than that of carbon dioxide (IPCC 2007) and is known to cause destruction of stratospheric ozone (Granli and Bøckman 1994). Nitrous oxide is responsible for 60% of global agricultural GHG emissions (Smith et al. 2007). Agricultural soil is the greatest single source of N_2O emissions (Environment Canada 2008).

Improving cropping practices can result in reductions of N_2O from agricultural soil (Zebarth et al. 2008a). There are many inputs into agricultural soil that stimulate the processes responsible for N_2O emissions, such as the addition of mineral N fertilizer, biological nitrogen (N) fixation, and incorporation of organic or green manures and incorporation of crop residues (Baggs et al. 2000a; Baggs et al. 2000b). However, there is limited information on the influence of different crop rotations and soil amendments on N_2O emissions.

Nitrification and denitrification are the primary sources of soil derived N_2O emissions, but there are other processes that contribute as well, including nitrifier denitrification, assimilatory nitrate reduction, dissimulatory nitrate reduction and abiological processes such as chemodenitrification (Baggs et al. 2000a; Pathak 1999). Because nitrification and denitrification are the primary sources (Mosier 1998; Firestone and Davidson 1989), these processes will be discussed in more detail.

Nitrification is a two-step process that converts ammonium (NH_4^+) to nitrate (NO_3^-) with nitrite (NO_2^-) as an intermediate (Brady 1999; Wrage et al. 2001):

$$NH_4^+ + 1\tfrac{1}{2}O_2 \rightarrow NO_2^- + 2H^+ + H_2O + \text{energy}$$

$$NO_2^- + \tfrac{1}{2}O_2 \rightarrow NO_3^-$$

Nitrification occurs under oxic conditions (Wrage et al. 2001). This process is catalyzed by several different bacteria, *Nitrosomonas*, *Nitrococcus, Nitrospira, Methylococcus, Methylmicrobium* as well as certain types of Archea*,* all of which are known to oxidize NH_4^+ to NO_2^-, and *Nitrobacter* and *Nitrospira,* which are known oxidize NO_2^- to NO_3^- (Wrage et al. 2001; Leininger et al. 2006). The supply of NH_4^+, the energy source for these organisms, is often limiting and, as a result, directly influences the size of the bacterial nitrifier population (Firestone and Davidson 1989). The process of nitrification produces N_2O as a by-product of NH_4^+ oxidation. When N_2O is produced, NO_2^- is used as the alternative electron acceptor (Firestone and Davidson 1989; Wrage et al. 2001).

Denitrification is an anoxic process involving the stepwise conversion of NO_3^- to N_2 gas, with N_2O as a gaseous intermediate (Firestone and Davidson 1989; McTaggart et al. 1997; Zumft 1997; Fazzolari et al. 1998):

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

N_2O is an obligatory intermediate of the reaction (Wrage et al. 2001). Denitrifying bacteria are found in approximately 50 genera and are predominantly part of the *Proteobacteria* phylum (Rich et al. 2003). The majority of denitrifying bacteria are facultative anaerobes that can utilize NO_3^- instead of O_2 (Wrage et al. 2001). Denitrification occurs in anaerobic microsites, and these microsites occur when the O_2 demand exceeds the diffused supply (Pathak 1999). Under anoxic conditions, denitrifying organisms use NO_3^-, NO_2^-, NO and N_2O as terminal electron acceptors instead of O_2 (Firestone and Davidson 1989). NO_3^- availability is essential for the denitrification process to occur and nitrification also plays an important indirect role regulating the rate at which NO_3^- becomes available to the denitrifying bacteria (Robertson 1982).

There is a need for more extensive studies examining the effects of crop rotation on N_2O emissions (Chantigny et al. 2002; Vinther et al. 2004; Snyder et al. 2007; Drury et al. 2008). N_2O emissions and denitrification rates may vary considerably among crop species (Ruser et al. 2001; Petersen et al. 2006). Although not fully understood, this variability can be, in part, attributed to soil N availability as a result of fertilizer N application (Ruser et al. 2001; Petersen et al. 2006). Tillage practices, crop selection and associated crop rotations and fertilizer applications alter soil NO_3^- and soil available C (Meyer-Aurich et al. 2006). Similarly, crop species may vary in their influence on soil aeration related to differences in tillage practices, and differing rates of evapotranspiration (Guo et al. 2009).

Study 1: Snowdon 2010

The overall objective of this research was to determine how different potato rotations influence N_2O emissions through their influence on soil NO_3^-, soil C availability and soil aeration. This was accomplished by studying seven two-year potato rotations during both the potato production phase and the rotation crop phase of the rotations. Specific objectives of the research were to quantify denitrification and N_2O emissions from a series of seven two-year potato rotations, quantify the effect of seven two-year potato rotations on soil NO_3^- and NH_4^+ concentrations and relate these concentrations to N_2O emissions.

The experiment was established in 2007, and the measurements reported in this presentation were taken in 2008, at the Potato Research Centre, Fredericton, NB. Soils at the experimental site belong to the Research Station soil association (coarse loamy morainal ablational till over coarse loamy morainal lodgement till), and are classified as Orthic Humo-Ferric Podzols (Rees and Fahmy 1984).

The experiment used a randomized complete block design with nine treatments replicated four times. The treatments included seven two-year potato rotations (Table 1). In each case, the potato and rotation crops were managed as would be appropriate for potato rotations in New Brunswick. The two additional treatments were two of the same potato rotations, with rotation crops of barley and red clover, except that no fertilizer N was applied in the potato phase of the rotation.

Table 1. Experimental treatments for the establishment year in 2007, the potato phase of the rotations in 2008, and the rotation crop phase of the rotations in 2009.

Treatment	**2007**	**2008**	**2009**
1	Corn	Potato 193^Z	Corn
2	Soybean	Potato 193	Soybean
3	Canola	Potato 193	Canola
4	Italian ryegrass	Potato 193	Italian ryegrass
5	Potato	Potato 193	Potato
6	Barley	Potato 193	Barley
7	Barley	Potato 0	Barley
8	Red clover	Potato 193	Red clover
9	Red clover	Potato 0	Red clover

^{Z}Numeric value indicates the fertilizer N rate in kg N ha^{-1}.

In 2008, the experiment was hand-planted to hand-cut potato seed, cultivar Russet Burbank. Sampling was performed from all treatments in 2008. Fertilizer N was banded at planting approximately 7.5 cm to each side and 5 cm below the seed pieces as NH_4NO_3. Plots were six rows (5.5 m) by 20 m in length, with the two outer rows acting as guard rows. Standard commercial practices were used for disease, insect and weed control. No irrigation was applied.

N_2O and CO_2 flux measurements were made using a non-flow-through, non-steady-state chamber (Burton et al. 2008). All plants and plant material were removed from the inner collar area. Gas samples were collected over a 30 min deployment period, with samples collected at 0, 10, 20 and 30 min (Burton et al. 2008). Gas samples were collected by removing 20 mL of gas from the headspace of the chamber and injecting it into a pre-evacuated (to 500 millitorr) 12-mL Exetainer (Labco, UK).

N_2O and CO_2 measurements were taken approximately weekly from May 1 until November 4, 2008. Duplicate collars were installed in each plot in early spring and remained in place until planting. After planting, the collars were reinstalled in duplicate in each of the hill and furrow row locations of each plot.

Soil samples for soil mineral N were collected on each date that N_2O and CO_2 fluxes were measured. The soils were stored at 4°C and processed within 24 hours. A 25 g sub-sample of moist soil was extracted with 0.5 M K_2SO_4 using a 1:2 soil:extractant ratio and a shaking time of 30 min (Miller et al. 2008). Extracts were filtered and stored at -20°C pending analysis.

Time-weighted cumulative growing season emissions of N_2O and CO_2 were calculated by linear interpolation between measurements over a 188 d (1 May 2008 to 4 Nov. 2008) monitoring period. Nitrate exposure (previously defined as nitrate intensity) was calculated as the linear interpolation of the NO_3^- concentrations between sampling dates. It is expressed in units of g N d kg^{-1}, which combines both the magnitude of NO_3^- concentrations and the duration where they are present. This measure gives us a temporally integrated measure of the exposure of the soil microbial community to NO_3^- over the growing season. The units express the number of days (d) over which the microbes were exposed to the magnitude of NO_3^- (Burton et al. 2008).

N_2O emissions were temporally variable over the growing season (Figure 1) Preceding crop had a significant effect on N_2O emissions on five sampling dates after planting: May 28, June 2, June 9, June 16 and July 2, 2009. On May 28, N_2O emissions for a preceding crop of red clover (average of 21.4 g N_2O-N ha^{-1} d^{-1}) were approximately seven times higher than for all other preceding crops (average of 2.9 g N_2O-N ha^{-1} d^{-1}).

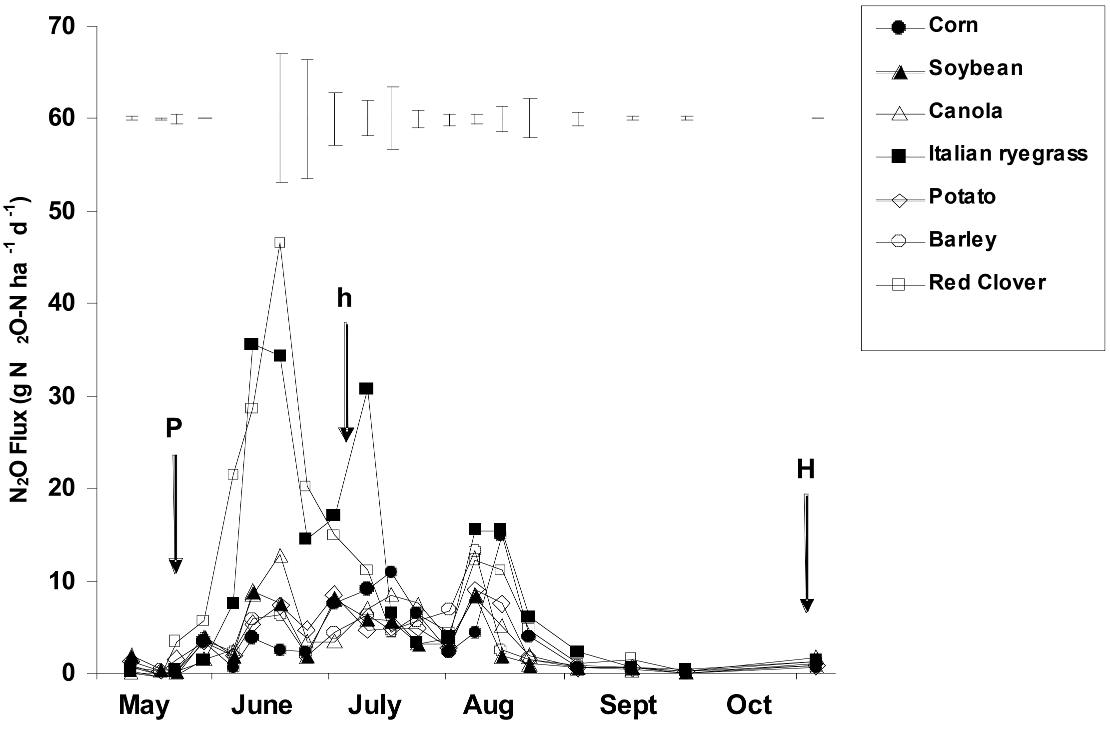

Figure 1.Temporal pattern of N_2O flux measured from potato production as influenced by preceding crop over the 2008 growing season. The arrow represents the date of planting and fertilizer application. Error bars represent ± 1 SE. The arrow "**P**" indicates time of planting, the arrow "**h**" indicates time of hilling and the arrow "**H**" indicates time of harvest.

On June 2, N_2O emissions were approximately six times higher for preceding crops of red clover and Italian ryegrass (average of 50.1 g N_2O-N ha^{-1} d^{-1}) compared with all other preceding crops (average of 7.7 g N_2O-N ha^{-1} d^{-1}). Similarly, preceding crops of red clover and Italian ryegrass produced approximately six times higher N_2O emissions (average of 41.5 g N_2O-N ha^{-1} d^{-1}) than preceding crops of corn, soybean, potato and barley (average of 6.5 g N_2O-N ha^{-1} d^{-1}) on June 9. Although there was a significant main effect of preceding crop on N_2O emissions on June 16, no treatment means were significantly different based on Tukey's pair-wise comparisons. On July 2, a preceding crop of Italian ryegrass produced approximately five times higher N_2O emissions (average of 32.0 g N_2O-N ha^{-1} d^{-1}) than preceding crops of corn, canola, soybean, potato and barley (average of 6.5 g N_2O-N ha^{-1} d^{-1}).

Cumulative N_2O emissions were positively correlated with cumulative CO_2 emissions and NE, but were not significantly correlated with AE or average WFPS (Table 2). The correlation was higher between cumulative N_2O and NE (r = 0.46) than between cumulative N_2O and cumulative CO_2 emissions (r = 0.32).

Table 2. Pearson correlation coefficients for the potato phase of the rotation in 2008.

	N_2O^Z	**CO_2**	**NE**	**AE**	**WFPS**
N_2O	1	+0.57*	+0.68*	-0.02	-0.38
CO_2	+0.57*	1	+0.44	-0.27	-0.67*
NE	+0.68*	+0.44	1	-0.19	-0.60*
AE	-0.02	-0.27	-0.19	1	+0.37
WFPS	-0.38	-0.67*	-0.60*	+0.37	1

*$P < 0.05$

^{Z}Cumulative N_2O emissions (N_2O), cumulative carbon dioxide emissions (CO_2), soil nitrate exposure (NE), soil ammonium exposure (AE) and average water-filled pore space (WFPS).

A multiple linear regression of cumulative N_2O emissions against cumulative CO_2 emissions, NE and average WFPS explained 60% of the variability in the N_2O emissions (Figure 2). Only cumulative CO_2 emissions ($P = 0.028$) and nitrate exposure ($P = 0.004$) explained a significant proportion of the variability in cumulative N_2O emissions in this regression.

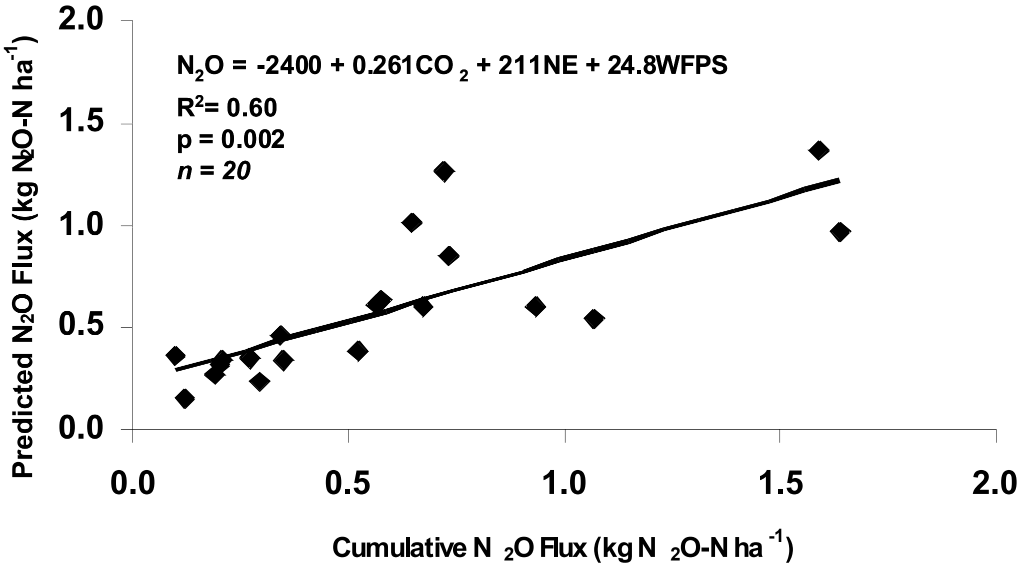

Figure 2. Multiple regression of predicted cumulative growing season N_2O emissions (N_2O; kg N_2O-N ha^{-1}) against measured cumulative growing season N_2O emissions for the potato phase of the rotations in 2008. Regression model includes terms for cumulative CO_2 emissions (CO_2; t CO_2-C ha^{-1}), nitrate exposure (NE; g N d kg^{-1}) and average WFPS (WFPS m^3m^{-3}). The regression was performed using treatment means, where hill and furrow locations were considered independently.

Nitrous oxide emissions from soil are associated primarily with the processes of nitrification and denitrification (Bateman and Baggs 2005; Granli and Bøckman 1994; Firestone and Davidson 1989). In the potato phase of the current experiment, most N_2O emissions occurred during two periods during the growing season. The first N_2O emission period occurred following planting and fertilizer application. During this period, soil NH_4^+ concentrations were high as a result of fertilizer application, and decreased rapidly over time suggesting that rapid nitrification was occurring, which likely contributed to N_2O emissions. However, the pattern of N_2O emissions as influenced by preceding crops was not consistent with the pattern of soil NH_4^+ concentrations. For example on June 2, preceding crops of red clover and Italian ryegrass had significantly higher N_2O emissions when compared with all other preceding crops whereas on the same date there were no significant differences in NO_3^- concentrations and a preceding crop of soybean had significantly higher soil NH_4^+ concentrations when compared with preceding crops of barley and canola. This period was also characterized by high soil NO_3^- concentrations, moderate values of WFPS, and in some cases elevated CO_2 emissions indicating increased soil carbon availability. Thus, although there was likely a contribution of nitrification to N2O emissions during this period, it is likely that denitrification was the primary source of N_2O emissions during this period.

The second period of N_2O emissions during the potato phase of the experiment occurred during a period of low soil NO_3^- and soil NH_4^+ concentrations, and with elevated values of WFPS (0.98 $m^3\ m^{-3}$) due to rainfall events with 109 mm of rain falling in a two week period. Elevated N_2O emissions at this time are consistent with denitrification as the primary source of N_2O emissions, and can be attributed to an increase in WFPS following the rainfall event (Ruser et al. 2006).

Choice of preceding crop had a significant effect on cumulative growing season N_2O emissions and on N_2O emissions measured on individual sampling dates during potato production. Preceding forage crops of red clover and Italian ryegrass resulted in significantly higher N_2O emissions when compared with preceding crops of corn, canola, soybean, barley and potato. Similarly, Ellert and Janzen (2008) found cumulative N_2O emissions from wheat to be significantly higher with a preceding crop of alfalfa compared with preceding crops of corn or fababean. Baggs et al. (2000a) also found that incorporation of Italian ryegrass and white clover residues resulted in significantly higher N_2O emissions when compared with incorporation of cereal, canola and winter wheat straw residues.

In the current study, the effect of preceding crop was evaluated on a potato crop receiving the recommended rate of fertilizer N applications. Consequently, one might assume that N_2O emissions would not be influenced by nitrate availability, and that the effect on the preceding crop on N availability would not be a factor influencing N_2O emissions. However, there was a significant effect of preceding crop on NE, and a strong positive correlation ($r = 0.68$) between cumulative growing season N_2O emissions and NE. For example, a preceding crop of red clover resulted in the highest NE values and the highest cumulative N_2O emissions. The above-ground red clover tissue had a low C:N ratio (17), suggesting these residues would readily decompose and increase soil N availability through net soil N mineralization (Baggs et al. 2000a). Interestingly, the red clover rotation crop returned a relatively low quantity of biomass (3.42 t ha^{-1}) with a moderate quantity of N (87 kg N ha^{-1}) when compared with other rotations crops. However, these values refer only to above-ground biomass whereas forage crops commonly also contain large quantities of below-ground biomass. For example, Bolinder et al. (2002) found that 50% of biomass was partitioned into the roots of perennial forage grasses and Zebarth et al. (2009a) found that, on average, 73% of Italian ryegrass dry matter production was stubble material. The elevated N_2O emissions and NE values for potato plots with a preceding crop of red clover can be attributed in part to the decomposition of the below-ground biomass containing N-rich root nodules.

In addition, a strong positive correlation was found between cumulative growing season N_2O emissions and cumulative growing season CO_2 emissions ($r = 0.57$). These CO_2 emissions are attributed primarily to soil respiration, but may also reflect root and tuber respiration. CO_2 emissions are used in the current study as a measure of soil carbon availability. A preceding crop of Italian ryegrass was found to have significantly higher N_2O emissions and CO_2 emissions when compared with all other preceding crops. This difference in CO_2 emissions can be attributed to the Italian ryegrass residues. There was a moderate quantity of Italian ryegrass residues incorporated (5.40 t ha^{-1}), which encompassed only the aboveground biomass. However, the belowground biomass may be an abundant C source. It is difficult to directly relate the measured above-ground biomass incorporation with C availability in the spring because it does not consider the below-ground biomass, and significant biomass decomposition may occur in the fall period after ploughing. Elevated C levels can cause denitrification rates to increase, thereby increasing N_2O emissions (Baggs et al. 2000a). Although there was only a moderate amount of plant biomass incorporated from the Italian ryegrass, the biomass had a high N content (162 kg N ha^{-1}) but did not result in high NE. This was likely due to the high C:N ratio of the Italian ryegrass residues compared with the other preceding crops. The C:N ratio of the Italian ryegrass residue was significantly higher when compared to the C:N ratio of the red clover. A C:N ratio of 32:1, can result in net immobilization. It is interesting to note that the above-ground canola residues, which returned similar quantities of biomass with a similar N content and C:N ratio to the above-ground Italian ryegrass residues, did not evoke a response in N_2O emissions as occurred with the Italian ryegrass. This may reflect differences in the quantity and quality of the below-ground biomass incorporated from the two different crops.

Rotation crops not only influence soil C availability, but also soil N availability. As documented by this study, without fertilizer N rate adjustment following certain forage crops, a substantial increase in N_2O emissions is possible. It is therefore recommended that choice of rotation crop be considered when making decisions with regard to fertilizer N application in the following year. Although some systems are in place to account for the effect of rotation crop on soil N availability, for example crop N credits, there is still significant room for improvement (Zebarth et al. 2009b). Development of systems to improve prediction of the effects of crop rotation on soil N availability would be useful in mitigating GHG emissions.

Study 2: Lynch et al. 2009

Organic potato production systems are characterized by extended rotations involving legume green manures. In these soils, the reliance on legume N from biological nitrogen fixation and relatively high quantities of stable organic matter from compost may regulate the availability of soil N and C needed for release of N_2O.

There is limited information available on the impact of organic potato rotations on N_2O emissions compared to conventional potato production systems. Lynch et al. (2009) were interested in the relationship between N supply and potato crop demand. They also researched how N_2O emissions differ with N source through various potato rotations.

The primary objectives of this research project were to examine the short and long-term effects of green manure type in different organic rotation sequences on N_2O emissions from potato production.

A long term study was established to examine the effects of two different five year organic potato rotations on N_2O emissions and PRS soil N supply to subsequent potato crops. The green manure sequences examined were 1) oats under-seeded with red clover, followed by red clover and 2) carrots followed by a pea, oat, and vetch (POV) mixture. Both of these sequences were followed by potatoes. N_2O emissions were measured approximately weekly over the growing season using non-flow-through, non-steady-state chambers (Burton et al. 2008). All plants and plant material were removed from the inner collar area. Gas samples were collected over a 30 min deployment period, with samples collected at 0, 10, 20 and 30 min (Burton et al. 2008). Gas samples were collected by removing 20 mL of gas from the headspace of the chamber and injecting it into a pre-evacuated (to 500 millitorr) 12-mL Exetainer (Labco, UK).

Soil N supply was measured using PRS^{TM} probes. The probes were installed randomly between mid-foot and furrow in each plot, enclosed in PVC root exclusion cylinders. The PRS^{TM} probes were removed and replaced in the same slot after 3 days initially and then following 4 successive 7-day intervals over a total of 31 days, prior to hilling.

The results of this study show that crop sequences in an organic potato production system can significantly affect soil N supply. A preceding crop of red clover resulted in a significantly higher soil N supply compared the POV sequence (Figure 3).

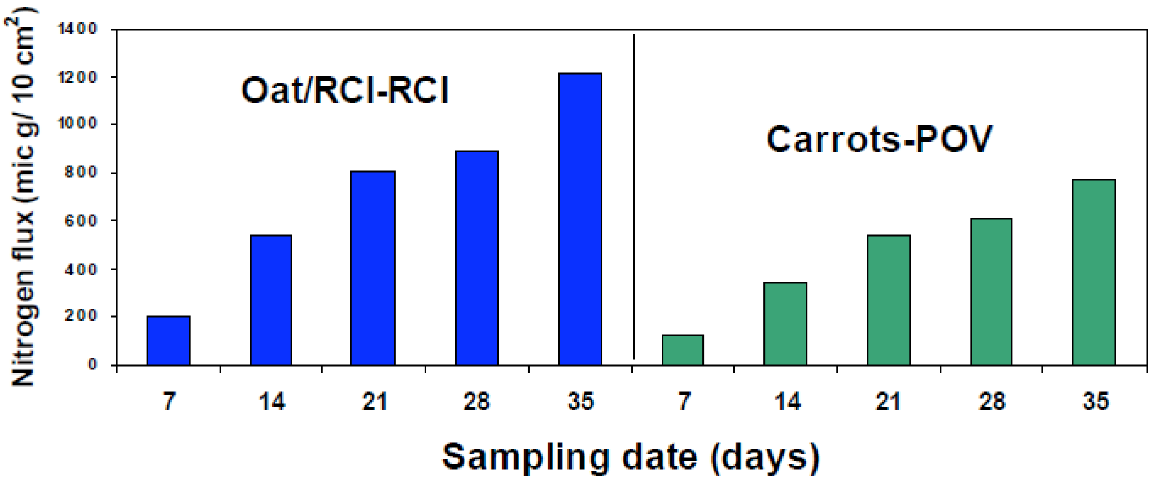

Figure 3. Cumulative soil N supply over the potato growing season as influenced by preceding crop.

This increase in soil N supply had a significant effect on soil-borne N_2O emissions with a preceding crop of red clover producing higher N_2O emissions when compared to the pea oat vetch rotation (Figure 3).

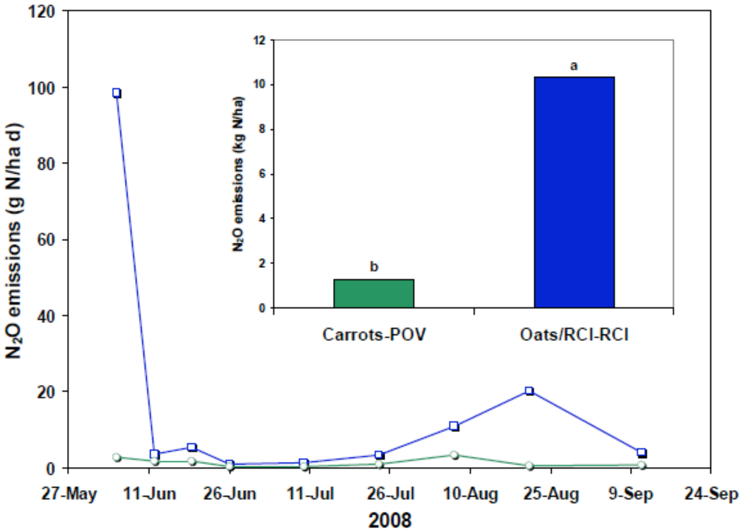

Figure 4. Temporal pattern of N_2O flux measured from organic potato production as influenced by preceding crop of red clover or a pea, oat and vetch mixture. The inlayed graph represents cumulative N_2O emissions over the growing season as affected by preceding crop.

Study 3: Schoenau et al. 2009

Controlled environment experiments were set up in 2008 to evaluate the effect of adding various biofuel and crop processing co-products to soil as organic amendments to increase soil fertility, crop growth, soil organic matter and microbial activity. Amendments evaluated included dehydrated alfalfa, wet distiller's grain, and thin stillage in comparison with urea fertilizer. Soil N supply and N_2O emissions were quantified.

The organic amendments included urea, alfalfa powder, wet distiller grains, and thin stillage. A total amount of 800 g of soil was incubated in pots with a surface area of 113.04 cm^2. Urea, alfalfa and wet distiller's grain were applied at rates of 200 kg N ha^{-1}. Each treatment was replicated four times.

All pots were brought to field capacity moisture content, and PRS^{TM} resin membrane probes were installed to adsorb nitrate and phosphate released in the soil over the incubation period. The pots were allowed to equilibrate and were placed in sealed incubation chambers. .

All the pots were placed into an airtight sealed container created from two PVC pipes 15 cm in diameter and 15 cm long with caps on each end. The two-part PVC container was joined together by a rubber airtight flange fastened with hose clamps. Using a 20-cm^3 syringe gas samples were extracted through a rubber septum inserted into the cap. Samples were stored in a 10-cm^3 evacuated vial until analysis via gas chromatography. Sampling was done every two days over the 10 day incubation. This experiment was completed in an incubation chamber set for 16 hr at 25 °C (day) and 8 hrs at 18°C (night). After each sampling time, the tops of the PVC containers were removed for 1 hr to allow natural airflow exchange between the chamber and the pots ensuring aerobic conditions.

The bioavailable NO_3-N, and NH_4-N supply rates in the soil were determined using Plant Root Simulator (PRS^{TM}). The anion and cation probes were inserted into the pots containing amended soil and remained installed for 10 days. At the end of incubation, the probes were removed form the soil and placed into plastic Ziploc^{TM} bags and transported to the lab. Probes were washed to remove all remaining soil particles and placed into a clean Ziploc^{TM} bag. 20-ml of 0.5 M HCl was added to each bag for one hour to elute the sorbed ions from the membrane surface. The eluant was then colorimetrically analyzed for NO_3-N and NH_4-N using Technicon^{TM} Auto-Analyzer II.

Fluxes of N_2O from the soil surface generally increased over the first few days of the incubation, followed by a levelling off or decrease (Figure 4). Rates of N_2O production were the highest and sustained over the longest period in the urea amended soil. As the NO_3-N content of the initial soil was quite low, and the moisture content was at field capacity or less, it would appear that the N_2O evolution observed over this time period is originating from the nitrification process. Of the organic amendments, wet distillers grain and thin stillage produced the highest rates of N_2O production per unit of N added. This can be attributed to a greater net release of NH_4-N by mineralization, due to the narrow C:N ratio of the amendment. Dehydrated alfalfa produced low amounts of N_2O, with total production of N_2O over the ten days that was significantly less than wet distillers grain or thin stillage.

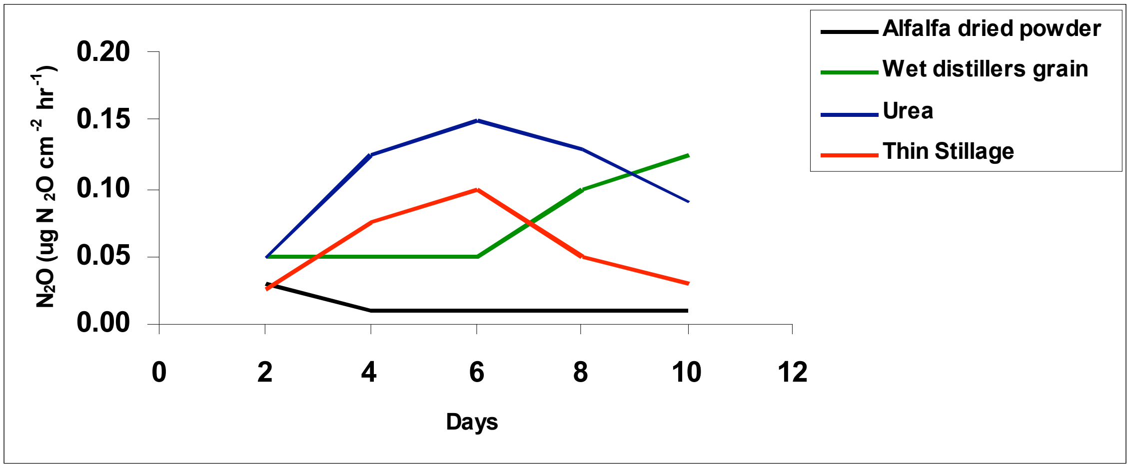

Figure 4. N_2O emissions evolved over a ten day incubation experiment from soil amended with bio-fuel by-products.

The supply rates of NO_3^- to the PRS^{TM} probes over the ten day period (Figures 5) were closely related to the patterns in N_2O production. The greatest supply rates of NO_3^- were observed in the urea treatment, which also resulted in the greatest N_2O emissions. Nitrification is likely the dominant mechanism and source of nitrous oxide in this incubation experiment. Some elevation in NH_4^+ supply rates was noted in the amendments wet distillers grain and thin stillage. This likely reflects a higher content of ammonium present initially in these amendments compared to alfalfa and urea, in which ammonium is formed by decomposition or hydrolysis. The effect of adding dehydrated alfalfa and wet distillers grains on the supply rate of NO_3^- over ten day of the incubation was limited with only small increases in the case of wet distillers grain, or decreases in the case of dehydrated alfalfa. This indicates that the release of available nitrogen from these amendments in the first few days was limited by some microbial immobilization, likely by a C:N ratio that was higher in the case of alfalfa than wet distillers grain. This also corresponded with low N_2O emission rates from the alfalfa amendment. More available N, and N_2O, would likely be released in following weeks as microbial decomposition of the amendments proceeded and C:N in the soil narrows.

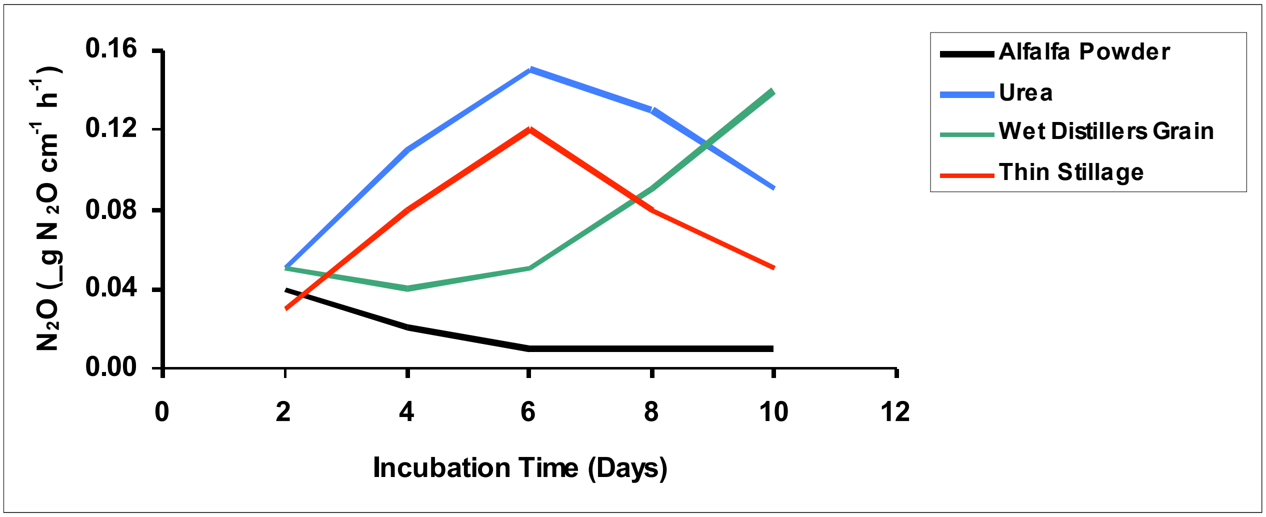

Figure 5. PRS™-probe supply rate measured over a 10 day incubation in soils amended with different bio-fuel processing by-products.

Conclusions

In all three studies the trend in N_2O emissions followed the trend in soil N supply. The incorporation of an N-rich residue resulted in increased soil N supply and N_2O emissions. C:N ratios of crop residues or soil amendments help predict net N mineralization or immobilization, an increase or decrease in the N economy, which can help predict N_2O emissions.