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Effect of nitrogen fertilizer rate on nitrous oxide emission from irrigated potato on a clay loam soil in Manitoba, Canada

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Increasing atmospheric concentration of nitrous oxide (N_2O) contributes to global warming and to the destruction of stratospheric ozone (Crutzen 1981; Ravishankara et al. 2009). Agricultural ecosystems are a major contributor to N_2O emissions, contributing an estimated 60-80% of total anthropogenic N_2O emission (Intergovernmental Panel on Climate Change (IPCC) 2006). Nitrous oxide emissions account for almost 60% of agricultural GHG emissions in Canada (Desjardins et al. 2005). In soils, N_2O is produced during the microbial processes of nitrification in aerobic conditions and denitrification in anaerobic conditions, with both processes being controlled by many factors, including available mineral N, available C, O_2, temperature, and water content (Granli and Bøckman 1994). Together, the nitrification and denitrification processes can also be linked to N_2O emissions as the former supplies nitrate to be reduced in denitrification and by nitrifier-denitrification in which nitrifiers reduce produced nitrite under O2 limitation (Kool et al. 2011).

Fertilizer N is essential for optimizing crop yields and can have impacts on N_2O emission (Beauchamp 1997). This is particularly important for the three Prairie provinces of Manitoba, Saskatchewan, and Alberta, as they contribute 82% of all fertilizer N used in Canada (AAFC 2002). Several studies on the Canadian Prairies have shown that field emissions of N_2O are affected by rate and timing of N fertilizer applications. For example, urea application at rates ranging from 40 to 120 kg N ha^{-1} consistently increased N_2O emissions over those from the control in a 4-year rotation cycle (barley-pea-wheat-canola) on a sandy clay loam soil in Saskatchewan (Malhi and Lemke 2007). Similarly, Burton et al. (2008a) found N fertilizer application at 80 kg N ha^{-1} increased N_2O emissions from wheat on clay loam and clay soils above an unfertilized control in Manitoba, while fall application tended to result in greater N_2O emissions than did spring application and granular source of ammonia N had no effect on emissions. Thus, limiting N_2O emissions from agricultural soils may be achieved by improved fertilizer management.

Instead of using the IPCC default (Tier I) value of 0.01 kg N_2O-N (kg^{-1} N-input) (1%; IPCC 2006), Rochette et al. (2008) developed a country-specific (Tier II) methodology and estimated regional fertilizer-induced emission factors (EF_{reg}) as 0.008 kg N_2O-N kg^{-1} N-input (0.8%) for the Black Soil zone of the Canadian Prairie region whereas a factor of 0.0172 N_2O-N kg^{-1} N-input (1.72%) was proposed for irrigated cropland (EF_{irri}).

Potato is one of the most intensively managed crops grown on the Canadian Prairies (Western Potato Council 2003). It requires substantial inputs of fertilizer N to optimize tuber yield and quality and tolerate diseases. Rates of 200 kg N ha^{-1} or more are frequently applied to potato crops in Canada (Zebarth et al. 2003).

Manitoba has the second-largest potato production acreage among Canadian provinces, with an estimated 30,000 ha in 2011 (Statistics Canada 2011). Unlike in Eastern Canada where potatoes are typically grown without irrigation and N fertilizer banded at planting, the majority of potato production in Manitoba is under irrigation and receives broadcast-incorporation of fertilizer N at planting and later at hilling.

Therefore, the objectives of this study were i) to investigate the cropping season temporal and spatial variability of N_2O emissions in relation to irrigation and fertilizer addition events and ii) to determine the relation of N fertilizer rate to N_2O cumulative emissions in an irrigated potato production system on a clay loam soil in the Black Soil zone of the Canadian Prairies in Manitoba.

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MATERIALS AND METHODS

This study was part of a three-year (2008-2010) field study that evaluated N dynamics in irrigated potato systems as influenced by cultivar and N fertilizer rate (Mohr et al. 2009). The study site was at the Canada-Manitoba Crop Diversification Centre in Carberry, Manitoba. The existing field experiments in 2009 and 2010 were used in the current study. Monitoring of N_2O emissions was conducted only in plots (3.8 m x 27 m) planted to the Russet Burbank cultivar, which is the most commonly grown cultivar in Manitoba for processing potato into French fries and patties.

N_2O gas sampling and analysis

Hilling is crucial to prevent tuber greening and facilitate harvest. Hilling, which is achieved to some extent with the planting operation, followed by a separate hilling operation conducted typically two to six weeks later, produces hills of increased soil porosity and furrows of reduced soil porosity. In the current study, N_2O emission rates were monitored separately for the hill and furrow position due to the distinctly different soil, nutrient and crop growth environments within these two positions, as they affect N_2O emissions (Ruser et al. 1998; Flessa et al. 2002, Burton et al. 2008b). The percentage of the covering area of hills versus furrows was estimated to be 50%-50% before final hilling and 60%-40% afterward.

The N_2O emission sampling was conducted using vented, two-piece (collar and lid), polyvinyl chloride (PVC) static cylindrical chambers (Tenuta et al. 2010).

Concentrations of N_2O in gas samples were determined by gas chromatography using a Varian CP-3800 gas chromatograph equipped with electron capture (ECD) detector and a Combi-Pal auto sampler system.

Cumulative emissions and emission factor

Growing season cumulative N_2O-N emissions from each sample position (collar) were calculated by the summation of daily estimates of N_2O emissions obtained by linear interpolation between sampling dates over 157-d (2009) and 159-d (2010) monitoring periods from spring through fall, with an assumption that the N_2O emission rate measured on a sampling date was representative of the average daily emission rate in that day. In both years, missing daily N_2O emission that occurred during the 6-d (2009) and 16-d (2010) periods between planting and the first sampling date was estimated.

The N_2O emission factor for the growing season period (EF_{gs}), expressed in percentage of N applied as fertilizer emitted as N_2O-N, was calculated as:

$$EF_{gs} = \frac{(N_2O_{fert} - N_2O_{control})}{\text{Applied N}} \times 100,$$

where N_2O_{fert} is the growing season cumulative N_2O emission (kg N ha^{-1}) of the fertilizer treatment, $N_2O_{control}$ is the growing season cumulative N_2O emission (kg N ha^{-1}) of Control, and applied N is the amount of N applied as fertilizer (kg N ha^{-1}). Yield based N_2O emission intensity was calculated as the ratio of cumulative N_2O to yield for each treatment plot expressed as g N_2O-N Mg^{-1} marketable yield.

Statistical analysis

The year and N application rate effects and their interaction on the growing season cumulative N_2O emissions and EF_{gs} were determined using the Statistical Analysis Software (SAS Institute, Inc., Cary, NC) and the procedure PROC MIXED, with plot replicate as a random effect and year and N rate as fixed effects.

RESULTS

Climate

Average air temperature May through October was approximately 1°C below the long-term normal in 2009 and similar to the normal in 2010 (data not shown). Total rainfall plus irrigation May through October was 345mm in 2009 and 480 mm in 2010, which is similar to and 40% above the total rainfall of the long-term normal without irrigation, respectively. In the 2009 growing season, precipitation was greatest in May and July, while in 2010 it was greatest in May (1.7 times normal). The amount of irrigation was approximately 50 mm in 2009 and 64 mm in 2010, amounting to 15% and 13% of total water input May through October of each year. The greater amount of irrigation in the wetter 2010 could be due to the higher air temperature in July and August compared to in 2009.

Mean daily N_2O emissions

The daily N_2O emission rate within sample positions was highly variable with the coefficients of variation (CV) in 2009 and 2010 ranging from 77-402% and 73-438%, respectively. In 2010 but not in 2009, N_2O emission increased by two weeks after fertilizer application, coinciding with the greatest rainfall event (45.2 mm, DOY 149; Data not shown). In both years, fertilizer N addition at hilling was followed by an increase in N_2O emission, which reached a maximum approximately 20 days in 2009 and 25 days in 2010 after application and then declined to levels similar to the Control. In 2009, the maximum field average emissions rates following N application at hilling were 17, 136, and 197 g ha^{-1} d^{-1}, for application rates of 80, 160, and 240 kg ha^{-1}, respectively. In contrast, the maximum emission rates following hilling in 2010 were lower than those in 2009, being 21, 47, and 91 g ha^{-1} d^{-1}, for application rates of 80, 160, and 240 kg ha^{-1}, respectively. In both years, the maximum emission rates following fertilizer application at hilling coincided with water addition events.

Growing season cumulative N_2O emissions and fertilizer-induced emission factor

The growing season cumulative N_2O emissions varied significantly with N application rate and year, as well as their interaction (Table 1). In 2009, N application at 160 and 240 kg ha^{-1}, but not at 80 kg ha^{-1}, increased the cumulative N_2O emission over that of the Control. In 2010, however, N application at all three rates increased cumulative emissions relative to the Control.

The average growing season cumulative emission for all treatments in 2010 was 1.7 times higher than that in 2009. In 2009, approximately 80% of total N_2O emissions occurred between DOY 180 and DOY 220 (i.e. over the six weeks following the N application at hilling). In 2010, however, a substantial contribution to the total emissions originated from fertilizer application at planting. The high emission periods after fertilizer addition at planting and hilling contributed 85% of the total N_2O emissions. Further, cumulative emissions increased linearly with fertilizer N rate for each year (Fig. 1). The increase in N_2O emissions per unit applied N fertilizer was slightly higher in 2010 than in 2009

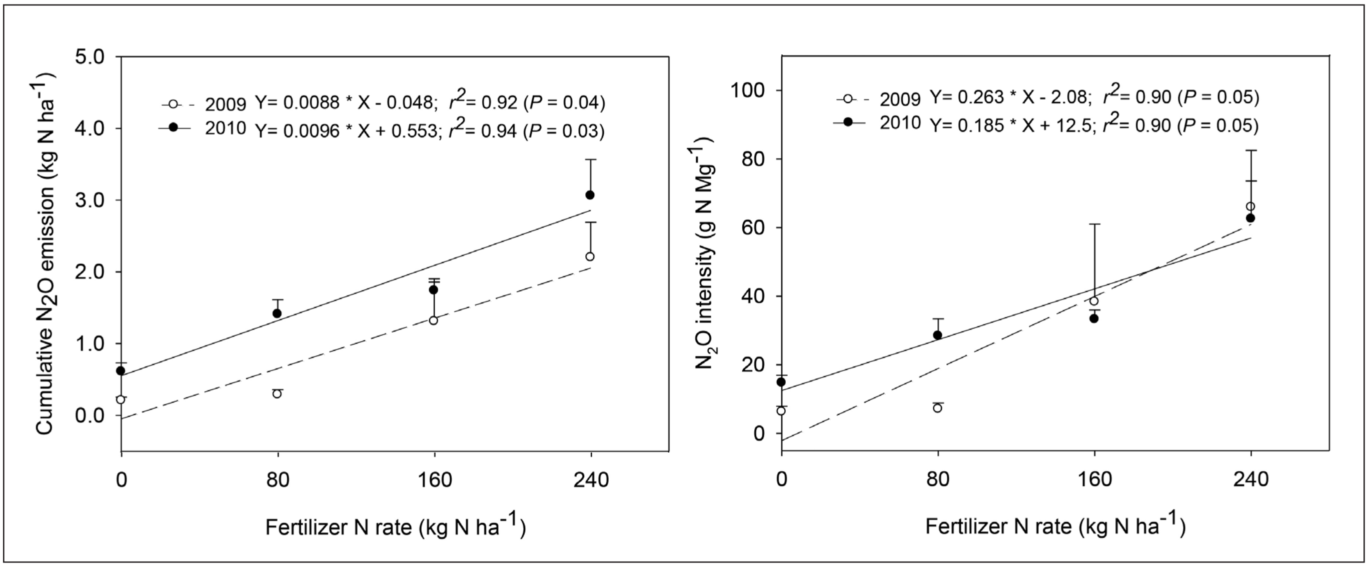

Fig.1. *Growing season cumulative N_2O emissions and yield based N_2O intensity as a function of fertilizer N rate in 2009 and 2010. Bars indicate +1 standard error (n = 8 for cumulative N_2O emission and n = 4 for N_2O intensity) of the mean.*

Table 1. *Growing season cumulative N_2O emissions and fertilizer-induced emission factor [EFgs] as influenced by fertilizer N rate in a potato field in 2009 and 2010. Cumulative emission values were calculated by linear interpolation between measurements over 157-d (2009) and 159-d (2010) monitoring periods.*

N Rate (kg ha^{-1})	**Cumulative N_2O emissions**			**EF_{gs}**		
	2009	2010	Avg.	2009	2010	Avg.
	---------------------- (kg N_2O-N ha^{-1} --------------------------			---------------------------- % ----------------------------		
0	0.21 c*	0.61c	0.41 d	-	-	-
80	0.29 c	1.41 b	0.85 c	0.10 b	1.00 a	0.55 a
160	1.31 b	1.74 ab	1.53 b	0.69 ab	0.71 a	0.70 a
240	2.20 a	3.06 a	2.62 a	0.83 a	1.02 a	0.93 a
Avg.	1.00	1.70	1.35	0.54	0.91	0.73
Analysis of Variance						
Sources	df	*Pr*≥zF		df	*Pr*≥zF	
N rate	3	<0.001		2	0.262	
Year	1	<0.001		1	0.004	
N x Year	3	0.022		2	0.119	

* Values within a column followed by the same letter are not significantly different (LSD) at a = 0.05 probability, n = 8.

likely resulting in the fertilizer rate and year interaction (Table 1). Similar to cumulative emissions, the yield based N_2O intensity also increased linearly with fertilizer rate each year (Fig. 1).

The calculated EF_{gs} ranged from 0.10% to 1.02%, with an overall average value of 0.73% (Table 1). The averaged EF_{gs} was higher in 2010 than in 2009 being 0.91 and 0.54%, respectively. Application of N fertilizer at 240 kg ha^{-1} significantly increased EF_{gs} over that of the 80 kg ha^{-1} N rate in 2009 but not in 2010. No fertilizer rate by year interaction was evident.

DISCUSSION

Our results show that N_2O emissions from irrigated potato increase with applied fertilizer N rate under the study conditions. Therefore, limiting N application rate to that required for most economical return on marketable yield can prevent N_2O emissions associated with application of N above most optimal rates.

Both cumulative emission of N_2O and yield based N_2O intensity increased linearly with fertilizer rate and consistent with previous studies in potato production systems (Ruser et al. 1998, 2001; Smith et al. 1998; Burton et al. 2008b). The main driver for differences in emission between fertilizer treatments would be the availability of NH_4^+ and NO_3^- in the soil as substrates for nitrification and denitrification processes. For Russet Burbank potato in this study, marketable tuber yield did not increase the 160 and 240 kg ha^{-1} N treatments, yet cumulative N_2O emissions and N_2O intensity tripled. The results suggest the total available N from soil and fertilizer at 80 kg ha^{-1} provided sufficient or near-sufficient supply of N for the potato crop. The absence of a positive yield response to fertilizer N at higher rates could be due to the relatively high soil organic C of 31 to 37 g kg^{-1} at the experimental site and thus likely N mineralization.

Another point that deserves consideration when applying the current study into the national inventory is that the current data were obtained on a single site of clay loam soil. While this soil texture type is representative of the potato soils in the tested area, it cannot be considered as representative of all soils in Prairies or even in Manitoba because of the range of soils (sand to clay loam) used for potato production. Soil texture is an important factor closely related to N_2O emissions and it is likely that a coarser-texture tends to cause less emission than a moderate-to fine-texture soil due to the lower organic C content and water holding capacity (Bouwman et al. 2002).

Consistent with the results of previous studies with potato and other crops (Zebarth et al. 2008; Smith et al. 1998; Ruser et al. 2001; McSwiney and Robertson 2005; Burton et al. 2008b; Glenn et al. 2010; Jiang et al. 2011), high rates of N_2O emissions shortly after ammonium-based N fertilizer additions were always associated with heavy rainfall (>20mm) or irrigation events in the current study. This suggests that denitrification being the dominant process responsible for increased N_2O emissions at these events. Soil moisture is one of the key environmental factors that drive N_2O emissions. Increased soil moisture could result in reduced soil aeration (Gillam et al. 2008), increased activity of denitrifying enzymes (Granli and Bøckman 1994) and consequently increased rate of denitrification.

Previous studies have shown the spatial distribution of emissions of N_2O within potato fields to be strongly affected by hilling, which produces areas of hills and furrows (Ruser et al. 1998, 2001; Flessa et al. 2002; Burton et al. 2008b; Buchkina et al. 2010). For the current study, results comparing hill with furrow position differed between years. In 2009, the increased N_2O emission following fertilizer and precipitation events occurred at hills but not at furrows. In 2010, however, fertilizer and precipitation events induced N_2O emissions from both hills and furrows, and that N_2O emission following fertilizer application at seeding were mainly from furrow position.

In the present study, in the relatively dry year of 2009 (total growing season precipitation was 15% less than climate normal), movement of broadcasted fertilizer toward hill position by the hilling operation could result in higher soil NO_3^- concentrations in the hills compared with the furrows. In contrast, the N fertilizer prior to planting was well incorporated and hills formed at planting were small relative to that formed by the subsequent hilling operation. In addition, the hilling implement in 2010 had caused less movement of soil in the furrow. Further, 2010 had greater water input with standing water noted in the furrows after rain and irrigation events, which could have enhanced N_2O production from fertilizer N at this position. Thus, hill versus furrow N_2O emissions are possibly affected by multiple factors (e.g. precipitation, soil factors, nature of the N application and hilling operations themselves).

Conclusion

By measurement of soil N_2O emissions over two growing seasons, the current study provides useful information on the response of N_2O emissions to fertilizer N rate under irrigated potato production on the Black Soil zone of the Canadian Prairies. Such information cannot only increase our understanding of temporal and spatial variation in N_2O emissions from the potato field in response to fertilizer N and irrigation or precipitation events, but also provide useful data for improving the Tier II approach for Canada. The linear regressions of the amount of N applied to the growing season cumulative N_2O emissions, as well as to the yield based N_2O intensity, suggest that avoiding applying fertilizer N beyond optimum rates for marketable yield can prevent the unnecessarily N_2O emissions associated with excess N rates. The increase in the emission rate following fertilizer addition was associated with water inputs, highlighting the importance of soil moisture level in affecting N_2O emissions. The spatial difference in N_2O emission between furrows and hills in response to fertilizer N or water input differed between years and were associated to the soil moisture conditions and perhaps type of hilling implement. These results suggest irrigation should be managed to avoid excess moisture conditions after application of N fertilizer to limit N_2O emissions. Further, the adjusted EF_{wy} in the current study was lower than the proposed IPCC Tier II protocol for irrigated cropland in Canada but close to that for the Black Soil zone. That irrigation was not conducted such that potential evapotranspiration equaled precipitation may be responsible for a lower than expected EF_{wy}. Thus, the results suggest it may not be suitable to assume precipitation equals potential evapotranspiration (PET) when estimating the EF for irrigated cropland. This study was conducted on a clay loam soil. The majority of soils used for potato cultivation in the Black Soil zone are of lighter texture. Thus, studies on lighter texture soil are required for a more robust assessment of nitrogen fertilizer EF across this zone.