4R NUTRIENT STEWARDSHIP:

Determining Manitoba-based reduction modifiers for the Nitrous Oxide Emission Reduction Program (NERP)

CANADIAN FERTILIZER INSTITUTE
INSTITUT CANADIEN DES ENGRAIS

4R nutrient stewardship

Project Final Report

Project Title:

Determining Manitoba-based reduction modifiers for the Nitrous Oxide Emission Reduction Program (NERP)

Monitoring Emissions at the TGAS MAN Study Site

Project Investigator

Mario Tenuta, Department of Soil Science, University of Manitoba

Acknowledgements

Funding for this project by the Manitoba Rural Adaptation Council (CAAP), the Canadian Fertilizer Institute, the University of Manitoba in support of the Canada Research Chair in Applied Soil Ecology, Koch Industries Inc., and Agrium Inc. is greatly appreciated. Funding for analysis of gases for the Potato N Rate study in 2009 was provided by the Manitoba Sustainable Agricultural Practices Program. Anhydrous ammonia and herbicide for the TGAS MAN site was provided by Viterra. This project funding provided the inertia for layering additional studies to examine the 4Rs of nitrogen fertilizer management in Manitoba such as the Potato Placement and Potato N Strategy studies included here. For those potato studies, funding from AAFC, NSERC post graduate scholarship and the Faculty of Graduate Studies (University of Manitoba) top up award to Sally Parsonage (M.Sc. student), and the Manitoba Productivity Enhancement Centre (MHPEC) is greatly appreciated.

The talent and dedication of research associates Dr. Haben Asgedom, Dr. Xiaopeng Gao, graduate students Krista Hanis, Sally Parsonage, technicians Brad Sparling, Matt Gervais, Jenna Rapai, Patrick Finnason, Prassana Adikari, Mervin Bilous, Tim Stem, Tek Sapkota, summer assistants Wole Akinremi Jr., Jonathan Kornelson, Kayla Orten, Camille Lacoste, Camille Gaubert, Thibault Dutroncy, Curtis Brown, William Shaw, Haben Asghedom Jr. and field staff of CMCDC Carberry, to completing this project is greatly appreciated. Trial management for potato studies by Dr. Ramona Mohr, Dr. Alison Nelson and their staff is greatly appreciated. The input and technical assistance of project collaborators, Dr. Don Flaten (U Manitoba; all aspects of project), Dr. Brian Amiro (U Manitoba; TGAS MAN site), Dr. Dale Tomasiewicz (AAFC; management of Potato N Placement Study), Dr. Ramona Mohr (AAFC; management of Potato N Strategy Study), Dr. Alison Nelson (AAFC; coordination of gas sampling for potato studies), and John Heard (MAFRI; extension) are greatly appreciated. Thank you to Brad Erb for use of his land for the Oak Bluff Red River Placement Study.

Mario Tenuta, Winnipeg, Manitoba.

PROJECT FINAL REPORTING FRAMEWORK
(As per Appendix C, Section 2 of the Agreement)

1). SUMMARY

(a) Title;

Determining Manitoba-based reduction modifiers for the Nitrous Oxide Emission Reduction Program (NERP)

(b) Name of Applicant(s);

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(c) Name of Institution or Organization;

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(d) Project duration (date of Project start up and completion);

July 1, 2010 through July 31, 2012

(e) Project Objectives;

Using field trials conducted in Manitoba determine nitrous oxide emission reduction factors for the following beneficial management practices:

1. Fall versus Spring anhydrous ammonia application (Fall vs. Spring),

2. Soil test nitrogen and most economical rate of nitrogen application (N Rate),

3. Banded versus broadcast-incorporation urea and enhanced efficiency fertilizer application (Placement).

(f) Activities carried out (a brief one or two page description of the accomplishments and a listing of project outputs, eg. business plan, thesis, conference paper, journal publication.);

Field Trials
Trials were initiated for each of the above objectives. A summary of the trials is presented in Table 1.

Field Trials Fall vs. Spring: The trial was located at the Trace Gas Manitoba Research Site (TGAS MAN) at the Glenlea Research Station, University of Manitoba, approximately 16 km south of Winnipeg. The research site was situated in the Red River Valley, a near-level (0 to <2% slope, typically <1 m km^{-1}), glaciolacustrine clay floodplain. The soils at the site were of the Red River association, consisting of a combination of Osborne and Red River series. The soils are classified as Gleyed Humic Vertisols (Canadian System). Bulk density and organic C content of the surface (0–0.2 m) soil were 1.2 Mg m^{-3} and 32 g kg^{-1}, respectively. The pH (2:1 water:soil mixture ratio) was 6.2 and carbonate minerals were absent in the surface layer. The particle size distribution was 60% clay, 35% silt, and 5% sand. We took advantage of existing infrastructure of plots and greenhouse gas measurement instrument at the site. Treatments consisted of fall vs. spring application of anhydrous ammonia for spring wheat in 2011 and corn in 2012. The trial started in fall 2010 with anhydrous application. Application occurred to separate 4 ha plots for the fall and spring anhydrous treatment. 100 and 160 kg N ha^{-1} were applied for spring wheat and corn, respectively, using farm-scale equipment. Allocations of treatments were switch in the two years so the fall 2010 treatment became the spring 2012 treatment, and the spring 2011 treatment became the fall 2011 treatment.

Field Trials Nitrogen Rate: The trial was located at the Canada Manitoba Crop Diversification Centre near Carberry, Manitoba (Potato N Rate). This study was part of a 3-yr (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 (CMCDC) (49°54′N, 99°21W) in Carberry, Manitoba. The existing field experiments in 2009 and 2010 were used in the current study. Monitoring of N2O 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.

The soil at the experimental sites is a clay loam (sand 32%, silt 40%, and clay 28%) soil in the Wellwood series being classified as an Orthic Black Chernozem. Initial characteristics of the surface (0-15 cm) soil in the fall prior to each planting were pH (H_2O) 5.9 and 6.2, organic carbon 37.2 and 31.4 g kg^{-1}, NO_3^--N 14.7 and 11.5 mg kg^{-1}, and $NaHCO_3$-extractable P 25 and 13 mg kg^{-1}, for the 2009 and 2010 sites, respectively. In keeping with soil testing recommendations, soil samples were collected from different plots and combined into one sample for determination of characteristics (Manitoba Soil Fertility Guide 2004). Soil texture was determined by the pipette method (Loveland and Walley 1991). Air-dried and sieved (2 mm) soil samples were extracted using 0.5 M $NaHCO_3$, with NO_3^--N concentration in the extract measured colorimetrically with an auto analyzer (Oakland, CA, USA), and P with an ARL 3410 inductively-coupled plasma (ICP) unit (Sunland, CA, USA). Total organic carbon was determined by wet oxidation.

The experimental design was a randomized complete block with four replicates. Fertilizer N treatments included an unfertilized check (Control) and application rates of 80, 160, and 240 kg N ha^{-1} as broadcast-incorporated urea, which was applied as a split application with 50% just prior to planting and 50% at hilling. Row and seed piece spacing was 0.95 m and 0.38 m, respectively. Other agronomic management followed practices appropriate for the local area potato production. Irrigation water from a groundwater source was applied by sprinkler based on monitoring the soil moisture level using tensiometers. Approximately 20-25 mm irrigations were performed for each application when the soil water content was below 65% available water capacity. Blanket applications of triple super phosphate (0-45-0) of 142 and 185 kg ha^{-1} and KCl (0-0-60) of 86 and 93 kg ha^{-1}, respectively in 2009 and 2010, were broadcast and incorporated prior to planting to meet crop needs. In 2010, potassium-magnesium-sulphate (KMag 0-0-22-22, 11% Mg) was also applied at 49 kg ha^{-1}. Application rates were based on a combination of provincial recommendations and knowledge of the site (Manitoba Soil Fertility Guide 2004). Fall soil nitrate test for the site was 77 in 2008 and 35 kg N ha^{-1} in 2009. Pesticides were applied as required to effectively control weeds, insect, and fungal diseases, using recommended pesticides and rates (Manitoba Agriculture, Food and Rural Initiatives 2009).

Planting occurred on 20 May 2009 (day of year (DOY) 140) and 15 May 2010 (DOY 135) using a Cheechi e Magli two-row planter (Budrio, IT). Hilling occurred on 24 June 2009 (DOY 175) and 23 June 2010 (DOY174), using a Grimme two-row rotary power hiller and a Lilliston two-row disc bedder (Bigham Brothers Inc., Lubbock, TX), respectively. Harvest occurred on 18 September 2009 (DOY 261) and 28 September 2010 (DOY 271) using a Grimme two-row harvester (Grimme GmbH and Co. KG, Damme, DE). A flail mower was used to chop the vines prior to harvest. Average marketable tuber yield (> 85 g) was 33, 41, 38 and 35 Mg ha-1 in 2009 and 41, 50, 52, and 49 Mg ha-1 in 2010 for the 0, 80, 160, and 240 kg N ha-1 fertilizer rates (Mohr et al. 2009, 2010). Yields were higher in 2010 than 2009 and were typical of the local commercial production.

Field Trials Placement: There were four trials with this objective. Two trials were duplicates of each other examining the effect of granular urea N placement and source. The trials were located at Oak Bank on a farm field and at the Carman Research Station (referred to collectively as Red River Placement Studies), University of Manitoba and repeated in 2011 and 2012 with planting to hard red spring wheat. The two other trials were located near Carberry, Manitoba, with planting to irrigated Russet Burbank potato and repeated in 2011 and 2012. One of the trials was located on the CMCDC-Carberry Station (Potato Placement) and one 2 km northeast of the station (N Strategy Study). Each trial was a randomized complete design with four replicates blocks. The trial plots in the second year were not situated on plots from the previous year.

For the Red River Placement Studies, the Oak Bank site was conducted on a Red River clay and the Carman site on a Hibson fine sandy loam soil.

The Potato Placement study was conducted on a Wellwood clay loam with organic matter 5.2%, 11 mg P kg^{-1} Olsen P, pH 6.1 and 29 kg N spring 2011 NO_3^-. The N Strategy Study was conducted on a Hallboro fine sandy loam with 15 kg ha^{-1} Olsen P, 35 kg N ha^{-1} spring 2011 NO_3^- (0-60cm). The Potato Placement and N Strategy Study plots were four rows (3.8m) wide by approximately 27 m long.

Greenhouse Gas Measurements

GHG Measurements Fall vs. Spring: Micrometeorological equipment to measure FN from the four plots was deployed at the site beginning in August 2005. A tunable-diode-laser absorption spectrometer (TGA100A, Campbell Sci. Inc., Logan, UT) trace gas analyzer (TGA) was set inside a trailer located at the junction of the four experimental plots. The TGA was further housed within an insulated, temperature-controlled (27.7 ± 0.1–0.5 °C) enclosure. The lead-salt tunable-diode-laser of the TGA (IR-N_2O/CO_2, Laser Components GmbH, Olching, Germany) was operated at a cryo-cooled temperature of −189.15 °C in a dualramp, jump-scanning mode and parameterized for the concurrent measurement of atmospheric concentrations of N_2O and CO_2 at 10 Hz above the four plots. The flux-gradient (FG) technique was used to determine F_N over 30-min intervals as $F_N = -K^*\Delta[N_2O]/\Delta z$, where K is the turbulent transfer coefficient or eddy diffusivity for N_2O, and Δ [N_2O] is the concentration gradient of N_2O over the vertical distance, Δ z. The 30-min mean N_2O flux densities, F_N, are reported as nmol N_2O m^{-2} s^{-1}. The eddy diffusivity (K) term was estimated using a similaritytheory, eddy-covariance-based aerodynamic method. A three-dimensional sonic anemometer–thermometer (CSAT-3, Campbell Sci. Inc.) was mounted at a height of 2 m to a tower in the center of a plot of each tillage treatment and used to calculate the variable's friction velocity (u*) and the sensible heat flux required to estimate K. Integrated similarity functions were applied to correct K calculations for stable and unstable atmospheric conditions based on the Obukhov length. Linear regressions between the sonic anemometer–thermometers from each management treatment indicated no significant difference in 30-min K values over the course of the study, so the average K was used in flux calculations for all plots. Snow depth, stubble and crop height (hc) was measured twice-weekly to weekly during the course of the study. These were used to estimate the zero-plane displacement height (d) and calculate the effective observation heights (z −d) used in stability corrections and determination of K. For periods of snow cover, d was assumed to be equal to the depth of snow, during the rest of the year it was assumed to be 0.66hc and interpolated between the manual observations.

For the calculation of Δ [N_2O], two stainless steel gas sample intakes (12.5 mm i.d.) were mounted 0.65 m apart and kept 1 m above the surface of each plot during non-cropped periods, and 1.2–2.2 × hc during the growing season. Samples were drawn down 4.3 mm i.d. tubing at a rate of 5 L min^{-1} to a manifold inside the trailer from which air from each plot and intake height was directed to the TGA. Half-hourly Δ [N_2O] were calculated over each four experimental plots sequentially, obtaining approximately one average 30-min gradient every two hours per plot as described by Glenn et al. (2010). Because of the size of the experimental plots (4 ha) and location of the FG towers in plot centers, fetch to observation height ratios of approximately 100:1 were maintained in all wind directions so most of the flux footprint originated within the treatment plot. Similar crop management within and outside of the experimental plots ensured that the K estimates represented an even wider area. The flux detection limit was about ±0.05 nmol N_2O m^{-2} s^{-1} based on a u* threshold of 0.12 m s^{-1} (described in the following section) and a minimum gradient detection level of ±0.045 nmol mol^{-1}, determined as the standard deviation of measurements when the intakes were placed at the same height. The detection limit varies slightly with stability and the measurement height adjustments.

Field operations (tillage, seeding, and harvest), system maintenance, mechanical malfunction and power disruptions caused interruptions in the collection of the flux data. The FN measurement system was not operational during April 2009 due to emergency flood preparations in the Red River Valley, and the spring-thaw flux following the spring-wheat crop is missing from the data set. After discarding these data, average 30-min Δ [N_2O] data coverage from the TGA was approximately 75% over the three study years. When including quality turbulence data from the sonic anemometer–thermometers (complete high-frequency half-hour time-series with no diagnostic warnings), data for the calculation of FN was 66% of possible half-hours. Data for Δ [N_2O] were rejected when the TGA operating temperature and pressure were outside of acceptable ranges (±0.5 °C and ±2 kPa, respectively). The Δ [N_2O] data were also rejected if the difference in the internal operating system pressure when switching between upper and lower intakes was greater than 20 Pa. Aerodynamic fluxes were rejected if the standard deviation of the 30-min mean upper or lower intake [N_2O] was greater than 20 nmol mol^{-1} dry air, and when the mean u* was less than thresholds previously determined acceptable for net CO_2 fluxes at the site: 0.15 m s^{-1} and 0.12 m s^{-1} for the maize; 0.18 and 0.12 m s^{-1} for the faba; and 0.15 and 0.12 m s^{-1} for the spring-wheat growing and non-growing seasons, respectively. After application of the u* filters, acceptable measured FN was 50% of possible 30-min periods. However, daily mean values of FN were available for approximately 70% of the days during the study. The average daily N_2O emissions are reported as g N_2O-N ha^{-1} d^{-1}.

GHG Measurements N Rate: 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. The percentage of the covering area of hills versus furrows was estimated to be 50-50% before final hilling and 60-40% afterward.

Sampling for N_2O emissions was performed between 26 May and 23 October (DOY 146-296) in 2009 and between 31 May and 20 October (DOY 151-293) in 2010, respectively. The time interval between samplings was mostly 3-7 d in 2009 and 2-3 d in 2010. The interval was occasionally increased to 11-12 d for samplings on DOY 173 and DOY 233 in 2009, and on DOY 279 in 2010. In 2009, only one measurement after harvest was taken on DOY 296. Determination of sampling date was dependent on the weather conditions and farming activities. The N_2O emission sampling was conducted using vented, two-piece (collar and lid), polyvinyl chloride (PVC) static cylindrical chambers (Tenuta et al. 2010). The collars measured 20.3 cm internal diameter by10 cm height. Lids covered with reflective aluminum foil were 0.6 cm thick with a diameter of 23 cm. Two collars were installed at approximately 3 cm depth on hill and furrow position for each plot. Collars on hill positions were placed between plants. The collars were installed a day prior to the first sampling and were covered only during gas sampling. The collars were installed permanently and only removed and re-installed for hilling. For sampling, lids were attached to the collars and 20-mL gas samples were collected through a rubber septum at regular intervals (0, 20, 40 and 60 min) using syringes (Becton-Dickinson, Franklin Lakes, NJ) and subsequently transferred to 12-mL thrice helium-flushed pre-evacuated to 0.04 MPA glass vials (Labco Exetainer, High Wycombe, UK). A layer of all purpose Silicon II was used on the top to seal the vials. Two 20-mL standard gas mixtures (N_2O, CH_4 and CO_2) were also injected into pre-evacuated vials prior to going to the field site, and handled in a same manner as other gas samples to confirm sample integrity during sampling and storage. All vials were transported back to the laboratory for analysis.

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. Analysis of a sample set was either repeated or the gas chromatograph column reconditioned and calibration redone if quality control samples were off by more than 5% of the expected concentration. The 60-min deployment time resulted in repression of N_2O accumulation with time for chamber locations of very active emissions. The N_2O emission rates (ng N_2O-N m^{-2} min^{-1}) were calculated using the HMR package implemented with the R language. The package recommends application of one of three regression approaches to estimate emission from the accumulation of N_2O during chamber deployment. A non-linear model is recommended if the accumulation of N_2O decreased with time. A linear model was recommended if the accumulation or dissipation of N_2O was consistent with time. An emission of zero is recommended in the absence of a clear trend in gas concentration with time. In this study we did not remove outlier concentration data from emission estimations or force negative emissions to zero. The application of the HMR package resulted in 19.7% of emissions estimated using a non-linear model, 79.2% a linear model, and 1.1% of the emission estimates forced to zero.

GHG Measurements Placement:
Measurements were conducted as described for the N rate study except rectangular chambers were used. For the Red River Placement study, chambers were positioned between plant rows (for mid-row banded treatments two between rows with fertilizer and two between rows without per plot). For the potato studies, two chambers were positioned on hills and two in furrows per plot.

Cumulative Emissions and Emission Factors

Cumulative Emissions Fall vs. Spring: Annual micrometeorological FN budgets for the treatments were estimated by summing the daily means with gap-filling of F_N by linear interpolation of missing periods (F_N-GF). The cumulative annual F_N budgets (F_N and F_N-GF) are expressed as kg N_2O-N ha^{-1} yr^{-1}.

To estimate fertilizer emission-factors (kg N_2O kg^{-1} fertilizer N applied) a background $\sum F_N$ estimate was required. We were unable to include a 0 N treatment in the experiment because the two other plots at the site were in perennial alfalfa/grass. Thus, we used the average of $\sum F_N$ for when plots did not receive fertilizer addition (faba bean year and perennial alfalfa/grass plots) which was 1 kg N_2O-N ha^{-1} yr^{-1}.

Cumulative Emissions N Rate and Placement: 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.

The N_2O emission factor for the growing season period (EFgs), 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_2Ofert 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.

Other Measurements

Basic soil characteristics (0-15cm), pre-plant, growing season and post-harvest soil inorganic N, soil moisture, above ground crop biomass and N uptake, yield and grain N were also determined for all studies.

Peer-review Publications Already Published from this Study

Xiaopeng Gao, Mario Tenuta, Alison Nelson, Brad Sparling, Dale Tomasiewicz, Ramona Mohr, and Benoit Bizimungu. 2013. Effect of nitrogen fertilizer on nitrous oxide emission from irrigated potato on a clay loam soil in Manitoba, Canada. Canadian Journal of Soil Science 93:1-11.

Communication

The project findings were present at the following meetings or tours;

Conference Presentations

Canada Grains Council Symposium (200 attendees). November, 2010, Ottawa, Ontario. Research Update on the Nitrous Oxide Reduction Protocol (NERP). Oral presentation by Mario Tenuta.

Manitoba Agronomists Conference (300 attendees). December, 2010, Winnipeg, Manitoba. What Does Reducing Soil Greenhouse Emissions Mean for the Farm? Oral presentation by Mario Tenuta.

Atlantic Fertilizer Institute Meeting, September, 2011, Moncton, New Brunswick. Research Update on the Nitrous Oxide Reduction Protocol (NERP). Oral presentation by Mario Tenuta.

Grow Canada, NERP Session (50 attendees). November, 2011, Winnipeg, Manitoba. Research on the Nitrous Oxide Reduction Protocol (NERP). Oral presentation by Mario Tenuta.

Great Plains Soil Fertility Conference (200 attendees). March, 2012, Denver, Colorado. Management practices to reduce emissions of nitrous oxide from fertilizer N: Studies from the Eastern Canadian Prairie. Oral presentation by Mario Tenuta.

American Society of Meteorology (200 attendees). June 2012, Boston, Massachusetts. Does Fall Anhydrous Ammonia Lead to Greater Nitrous Oxide Emissions Than Spring Addition? Poster presentation by Tek Sapkota.

United States Department of Agriculture – Enhanced Efficiency Fertilizer and Nitrous Oxide Emission Reduction Invited Workshop (25 attendees), August 2012, Fort Collins, Colorado. Managing N Fertilizers to Reduced N_2O Emissions under Wet Soil Conditions. Oral presentation by Mario Tenuta.

Field Days

TGAS MAN tour for Manitoba Farm Writers and Broadcasters Association (50 attendees). June, 2011. Hosted by Mario Tenuta, students and technicians.

TGAS MAN and Red River Placement site visit by Canadian Fertilizer Institute (2 attendees). July, 2011. Hosted by Mario Tenuta.

TGAS MAN and Red River Placement site visit by International Plant Nutrition Institute (2 attendees). July, 2011. Hosted by Mario Tenuta.

Potato N Studies public tour at CMCDC, Carberry (50 attendees). July, 2011. Hosted by Mario Tenuta.

TGAS MAN and Red River Placement site visits by Ray Dowbenko of Agrium. August, 2011. Hosted by Mario Tenuta.

TGAS MAN tour for Young Farmers of Canada (60 attendees). June 2011. Hosted by Mario Tenuta.

Potato N Studies tour for Manitoba Farm Press Writers Association at CMCDC (50 attendees). June, 2012. Hosted by Sally Parsonage.

TGAS MAN Field Day (attendees 60 including from MRAC). August, 2011. Hosted by Mario Tenuta, students and technicians.

Potato N Studies public tour at CMCDC, Carberry (50 attendees). July, 2012. Hosted by Sally Parsonage.

Enhanced Efficiency Fertilizers and the 4Rs to Reduce Losses of Fertilizer N (80 attendees). Soil & Manure Management Field Clinic. August, 2012. Glenlea, Manitoba. Hosted by John Heard and Mario Tenuta.

TGAS MAN tour by Canadian Farm Writers Federation (35 attendees. September, 2012. Hosted by Mario Tenuta.

TGAS MAN tour for New Democratic Party Caucus (10 attendees). October, 2012. Hosted by Mario Tenuta, students and technicians.

Other Presentations

Greenhouse Gas Studies in the Soil Ecology Laboratory, University of Manitoba. Presentation at the Inner Mongolia Agricultural University (55 attendees). June, 2011. Oral presentation by Mario Tenuta.

Nitrous oxide studies at The University of Manitoba. Meeting with Matt Wiens of MAFRI. July, 2011. Hosted by Mario Tenuta.

Potato Studies in the Soil Ecology Laboratory (25 attendees). Manitoba Horticultural Productivity Enhancement Centre MHPEC Research Day. December, 2011. Oral presentation provided by Mario Tenuta.

Research Update on Nitrous Oxide Studies by The University (35 attendees). Viterra Agronomists Day, Winnipeg, Manitoba. December, 2011. Oral presentation by Mario Tenuta.

Nitrous Oxide Studies at The University of Manitoba for Modelling Efforts (8 attendees). Agriculture and Agri-Food Canada Greenhouse Modelling Group. October, 2012. Ottawa, Ontario. Oral presentation and discussion hosted by Mario Tenuta.

Management Practices to Reduce Emissions of N_2O from Fertilizer N (20 attendees). Manitoba Soil Fertility Committee Annual Meeting. June, 2012. Oral presentation given by Mario Tenuta

Potato Studies in the Soil Ecology Laboratory (15 attendees). Manitoba Horticultural Productivity Enhancement Centre (MHPEC) Research Day. December, 2012. Oral presentation provided by Mario Tenuta.

4R and Enhanced Efficiency Fertilizer Studies. Meeting with Dow AgroSciences, Canada (2 attendees). December, 2012. Winnipeg, Manitoba. Oral presentation by Mario Tenuta.

Evaluating the 4Rs of Fertilizer Management to Reduce N_2O Emissions in Manitoba (30 attendees). Department of Soil Science Seminar. November, 2012. Oral presentation by Mario Tenuta.

Student Theses
Two theses are in progress

Sally Parsonage, M.Sc. Nitrous oxide emissions reductions with beneficial nitrogen fertilizer management practices of irrigated potato in Manitoba. December 2013 expected completion. Sally is using the Potato Placement and N Strategy trials as the basis of her thesis.

Krista Hanis, Ph.D. Studies of net greenhouse gas emissions from a subarctic and an agricultural soil in Manitoba. December 2014 expected completion. Krista is using the TGAS MAN trial for one chapter in her thesis.

(g) A copy of project outputs as per (f).

See accompanying published manuscript and copy of presentation to Department of Soil Science Seminar Series (Nov 2012) which summarized the latest information from the project.

2.) RESOURCES

(a) Summarize the project contributions for the entire project by source, as follows:

CAAP	Applicant/ Industry Cash	Applicant In kind	Provincial/ Municipal Cash	Federal Cash
230,650	38,850 (Soil Ecology U Manitoba) / 60,000 (Canadian Fertilizer Institute). Additional projects contributions 10,000 Koch Industries for costs of adding a broadcast incorporated SuperU treatment in Red River	Not determined *	45,000 from the Manitoba Sustainable Agricultural Practices Program for gas analysis in 2009	Additional project contribution, AAFC contract (2011/2012 and 2012/2013) services of 90,000 for

	Placement Study in 2012/2013, 4,000 from Manitoba Horticultural Productivity Enhancement Centre for labour and travel expenses for inclusion of potato studies / 12,000 Agrium for contribution to gas analyses on all projects with ESN. 5,000 fellowship (2012/2013) from Faculty of Graduate Studies, University of Manitoba, to M.Sc. student Sally Parsonage.		from the Potato N Rate Study. Additional project contribution, 30,000 from Province of Manitoba Agricultural Sustainability Initiative (2011/2012 and 2012/2013) for inclusion of gas analysis of Potato N Placement studies	inclusion of gas analyses of Potato N Strategy studies. 19,000 NSERC Graduate Scholarship (2012/2013) to Sally Parsonage working on her M.Sc. with the Potato Studies.

* not determined because of difficulty in quantifying dollar value of infrastructure in the Soil Ecology Laboratory (gas chromatographs, gas handling equipment, laboratory equipment), University of Manitoba (field equipment, storage facilities, soil processing equipment) and Canada Manitoba Crop Diversification Centre (Carberry, Manitoba; field equipment, staff time contribution, crop supplies and inputs, irrigation) that helped to make this a successful project.

(b) If possible, provide an estimate of the potential financial impact on the sector *(e.g., amount of increased investment, sales, exports, cost savings*) if widely adopted or applied, or fully implemented.

This is hard to estimate right now because the results are so recent and there are still four site years that require completion of analyses for activities beyond July 2012. The project results will be considered in improving the NERP and are available to MAFRI to promote with CFI 4R N fertilizer management to limit N losses to the environment. Dr. Tenuta has already been contacted by Mathew Wiens of MAFRI to incorporate timing and placement recommendations in the Provincial recommendations for minimizing N_2O emissions from soil.

3). OUTREACH AND DISSEMINATION

Indicate who were the ultimate beneficiaries of the project and what level of contact was there with them (*eg. 150 producers, 70 representatives of government, 25 members of academia*).

Indicate vehicles used to disseminate the information to the ultimate beneficiaries and any feedback/uptake where applicable.

The following are groups that benefitted from the project by visiting the site and/or hearing of the findings in presentations.

A detailed listing of dissemination vehicles was given previously (Section 1f). The ultimate beneficiaries of the project are summarized here.

4). RESULTS

(a) Provide conclusions of the project including the significance of results and discussion of the project results including an explanation or interpretation of such results and indication of any unanticipated factors that affected the results of the project;

Results Fall vs. Spring:
Nitrous oxide emissions at the TGAS MAN site prior to this study (2006-2010) showed fluxes to be concentrated in two short periods, after fertilizer addition during planting and in spring when soil thaws from winter (Figure 1). The year without N fertilizer application resulted in no post fertilizer emission as well as no thaw emission the subsequent year. Emission post fertilizer application was higher on plot 3 than 2 in 2006, 2008 and 2010 but lower in 2009. Plot 3 received anhydrous ammonia in fall 2010 with no resulting emissions that fall or over winter (Figure 1). However, emissions during spring thaw in 2011 was greater for Plot 3 than Plot 2 that did not receive fall anhydrous ammonia. Anhydrous ammonia application to Plot 2 in 2011 resulted in a large peak in emission while there was not emission from Plot 3 at this time. Application of anhydrous ammonia was done on Plot 2 in fall 2011 resulting in no appreciable fall or winter emissions. However, as seen before with fall application, there were emissions at spring thaw for this treatment. Several weeks post planting in 2012, several large rains occurred beginning of June resulting in extremely large emissions for the spring treatment and lesser so for the previous fall treatment. The temporal pattern of NH_4^+ and NO_3^- concentration in soil was differentially affected by application treatments and generally were dramatically reduced by crop uptake (Figure 2). In particular fall application in 2011 resulted in elevated NO_3^- that fall and after spring thaw. This NO_3^- was likely related to the greater emissions with fall treatment at spring thaw. In 2011, spring wheat yield was generally very low (Table 2) for the study because of very wet spring and post plant conditions resulted in weed growth in spring and then after planting without ability to traffic soil to apply herbicide. The yield of corn was very good with no difference between fall and spring application. Over both crop years, spring anhydrous ammonia application resulted in greater total emissions (Table 3). After accounting for 1 kg N_2O-N ha^{-1} background emission, there was an overall reduction of 36% in emissions with fall than spring application of anhydrous

ammonia for the 2011 and 2012 crop years. However, note because of the timing of this report, for the 2012 crop year, spring thaw emissions in 2013 are not included.

Results Potato N Rate:

In 2010 but not in 2009, N_2O emission increased by two weeks after fertilizer application, coinciding with the greatest rainfall event (45 mm, DOY 149; Figure 3). 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. For example, in 2009, the maximum emission rate occurred on DOY 198, coinciding with the rainfall of 33 mm on DOY 190, which was also one of the largest water addition events in that year. In 2010, the maximum emission rate was recorded on DOY 151, coinciding with the 45 mm rainfall on DOY 149 in that year. Also, the second highest emission rate in 2010 occurred on DOY 197, coinciding with the water additions by irrigation of 19 mm on DOY 196. In 2009, an N_2O emission episode occurred after fertilizer applications and water addition events (DOY176-216) for the hill but not for the furrow position. In 2010, however, N_2O emission episodes occurred after fertilizer applications and water addition events (DOY140-161, DOY 180-216) for both hill and furrow positions. The emission episode following fertilizer application before planting was much more evident in the furrow than in the hill position, though because of the gap between sampling times it cannot be certain that emission may have already occurred and subdued for the hill positions.

The growing season cumulative N_2O emissions varied significantly with N application rate and year, as well as their interaction (Table 4). 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 (Figure 4). The increase in N_2O emissions per unit applied N fertilizer was slightly higher in 2010 than in 2009 likely resulting in the fertilizer rate and year interaction (Table 4). Similar to cumulative emissions, the yield based N_2O intensity also increased linearly with fertilizer rate each year (Figure 4).

The calculated EF_{gs} ranged from 0.10% to 1.02%, with an overall average value of 0.73% (Table 4). 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.

Results Red River Placement:
Emissions occurred within 3 weeks of fertilizer application for all N treatments (Figure 5). Generally peak emissions were higher at the Carman site and with broadcast urea (Figure 5). The duration of this emission event was greater for side than mid-row banded treatment. Cumulative emissions related well to calculated nitrate intensity values with urea and broadcast treatments showing the most intensity and emissions (Figure 6). Cumulative emissions were Urea Broadcast >= Urea Side band = urea mid-row > SuperU mid-row = ESN mid-row > Check (Table 5). Banding reduced emissions compared to broadcast incorporation of urea by 24% and 43% for side and mid-row banding, respectively. Further, ESN and SuperU mid-row banded reduced emissions by 74% of the broadcast incorporation treatment.

Results Potato Placement:
In general, emissions from broadcast incorporated treatments were earlier than with banding treatment (Figure 7 and 8). Emissions from band treatments were slightly higher 40 days into the study period. The highest emission was observed for the ESN 100 Band treatment, however there was much greater variability for this sampling (Figure 7).

Estimates of cumulative emissions for the treatments were weakly significant (P=0.096). However, banded treatments were all lower than their respective broadcast incorporated treatments (Table 6). In this respect, results here are similar to other studies in the Red River valley we recently conducted showing banding to reduce emissions compared to broadcast incorporation. The results of this study contrast those in that ESN did not reduce emissions compared to urea. Emission factors ranged from 0.94 to 2.62% of N addition (Table 6). As seen in the Red River Placement study, banding of urea reduced emissions by 24% with the decrease being even greater, 47%, for banding with ESN.

Results Potato N Strategy:
Emissions of N_2O from N treatments began to increase two weeks following addition and planting and generally peaked three weeks following planting (Figure 9). An exception being the fertigation strategy that had a more uniform

scheduling of N application (Fertiligation 2) than the other fertigation strategy (Figure 9).

Generally, emissions were lower for this study site than for other studies we have conducted at the CMCDC-Carberry station. In this study, cumulative emissions were highest with Single application treatments, followed by Fertigation and then the Split treatment (Table 7). Emission factors are generally very low compared to other studies we have conducted. Interestingly, the practice of split urea application that most growers use had the lowest emissions. The fertigation treatments had the highest emissions which in light of increasing adoption of the practice means emissions from potato systems in Manitoba are increasing.

(b) What are the short-term outcome(s) expected at the end of the project:

- see Table 8 for summary of short-term outcomes

- Late fall application of anhydrous ammonia produced 36% less N_2O than spring application. Fall application increased the subsequent spring-thaw emissions but the early season emissions were much reduced than spring application. This is a very interesting finding and contrary to the NERP that promotes spring than fall application to reduce N_2O emissions. However, the 2010/11 season was extremely wet, and thus conclusions for that season may not be typical thought they agreed well with the drier 2011/12 season results. The findings have very important implications to Prairie Canada which fall application of N fertilizers is commonly done for several advantageous reasons for growers. The results should cause a rethinking of the assumption that fall applications increase nitrous oxide emissions. That assumption has been based on corn-belt and eastern Canada research where soil does not freeze, and fall soil temperatures drop rapidly in Prairie Canada compared to other areas.

- The emission of N_2O increased linearly with application rate for irrigated potato. There is debate in the literature if emissions increase exponentially with rate of N fertilizer addition. Thus it seems, applying a constant emission factor to N fertilizer addition is OK for irrigated potato in Manitoba.

- Banding of fertilizer N for spring wheat and potato crop production reduced N_2O emissions. Emissions were reduced by about 25% with side banding in the systems. For spring wheat production, mid-row banding had even further reductions being about 45%. The findings substantiate the NERP predictions, though the reduction in emissions factors may be too conservative in the protocol.

- The lower emissions with banding can be even further reduced by changing the source of N to enhanced efficiency fertilizer products such as ESN and SuperU. The reduction from broadcast incorporated urea was considerable, about 75%, when ESN or SuperU were mid-row banded for spring wheat. The reduction was still considerable for irrigated potato when ESN was side banded, being about 50%. The findings substantiate inclusion of enhanced efficiency fertilizer products for reducing emissions when banded.

- The standard practice potato growers in Manitoba currently employ, split application of urea, had the lowest emissions than single full application of urea or ESN at planting or metering N additions through the season with fertigation. This finding is important because fertigation is becoming more common in Manitoba where most processing potatoes are irrigated. Thus, emissions of N_2O may be increasing because of greater adoption of fertigation. The NERP currently does not consider the impact of fertigation. The protocol assumes metering N additions to coincide with crop demand is effective to reduce emissions. Under irrigated conditions, the assumption may not be suitable.

(c) Next steps (if applicable);

- See Table 8 for short-term next steps

- Obtain funding to complete gas ($30,000), soil ($5,000) and plant analyses ($5,000) from past July 2012 for the Red River Placement, Potato N Strategy and Potato Placement studies to complete the 2012 crop year monitoring. This will complete those studies.

- Obtain funding ($7,500) for a research associate to write up the Red River Placement study for submission of a peer-review paper.

- Promote banding of fertilizer N to reduce emissions in irrigated potato and annual crop production in the Red River Valley.

- Review the NERP to determine if banding practices should result in greater credit reduction in emissions.

- Conduct studies on other soils in Manitoba if late fall application of N fertilizers also reduces emissions. The results indicate the NERP is in error in crediting spring application of fertilizer N for the Red River Valley.

- Conduct studies to stack enhanced efficiency fertilizer products with late fall application to reduce emissions even much more so than spring application. Then determine if stacking should result in a credit in the NERP.

- Conduct further studies if fertigation increases emissions because the results here indicate emissions from potato production in Manitoba is increasing with greater adoption of fertigation practices.

- Examine the NERP to determine if stacking of placement and timing with enhanced efficiency products should result in even greater credits than currently used.

- Have the two students complete their theses and then publish the Red River Placement, Potato Placement and Potato N Strategy papers in peer-review journals.

(d) Include any publications, documents or materials for communications and all promotional activities as well as any and all other material for public distribution generated by the project, or which will be disseminated in the future.

See appended published manuscript and latest presentation summarizing the project findings.

Which of the following describe the potential long-term benefits from this project?

--- reduced production or processing costs through optimizing N additions for yield and lower losses to the environment

--- other (specify) – benefit to environment of lower greenhouse gas emissions from agriculture

5). FOLLOW UP

(a) Indicate any project follow-up that is planned (e.g., dissemination of results, full implementation of project, etc)

Towards Full Implementation of the Project:
Complete analyses for past July 2012 for Potato N Studies and Red River Placement. A request will be made to the Canadian Fertilizer Institute through its current Science Cluster for funding.

Dissemination of Results: Peer-review Manuscripts:
Effect of banding and enhanced efficiency fertilizers on clay soil for spring wheat on N_2O emissions.

Effect of banding and enhanced efficiency fertilizer on irrigated potato soil on N_2O emissions.

Emissions from fall and spring application of anhydrous ammonia.

Resulting New Projects:
Applications to NSERC and the Canadian Fertilizer Science Cluster to Agriculture and Agri-Food Canada on stacking of enhanced efficiency fertilizers with late fall application of anhydrous ammonia and granular urea to limit emissions of N_2O with support from Agrium Inc., Dow Agrochemicals and Koch Industries.

(b) Indicate questions on implementation/commercial impact that may be appropriate to include in a follow-up survey to your organization one year after project completion.

Was the University of Manitoba successful in obtaining funding to complete analyses?

Was the University of Manitoba successful in obtaining funding to write up the project results for peer-review publication?

Did the results of the second year of study for the Red River Placement, Potato Placement and Potato N Strategy agree with the first year results?

Was the Canadian Fertilizer Institute and the University of Manitoba successful in obtaining funding for stacking of enhanced efficiency fertilizers and late fall application of N fertilizers?

How has the Province of Manitoba, used the project results to promote farming practices that reduce greenhouse gas emissions?

How have the results been incorporated into the NERP?

Table 1. Summary of studies conducted in this project.

Objective	Trial Name	Duration	Locations	Treatments	Crops
Fall vs. Spring	TGAS MAN	Fall 2010-2012	Glenlea Research St.	Fall/spring anhydrous NH_3	2011- spring wheat with 100 kg N ha^{-1}, 2012- corn with 160 kg N ha^{-1}
N Rate	Potato N Rate	2009-2010	CMCDC Carberry St.	0, 80, 160, 240 kg N ha^{-1} split urea broadcast incorporated	Irrigated Russet Burbank potato
Placement	Red River Placement	2011-2012	Oak Bank and Carman Research St.	0, 80 kg N ha^{-1} of urea, ESN and SuperU broadcast incorporated, and urea, ESN and SuperU side- and mid-row banded (SuperU only 2012, others 2011 and 2012)	Hard red spring wheat
Placement	Potato Placement	2011-2012	CMCDC Carberry St.	0, 100, and 200 kg N ha^{-1} broadcast or side-banded urea and ESN (2011 no urea 100 kg N ha^{-1})	Irrigated Russet Burbank potato
Placement	Potato N Strategy	2011-2012	Carberry	0 and 180 kg N ha^{-1}, split urea, single urea, single ESN, and two fertigation schedules	Irrigated Russet Burbank potato

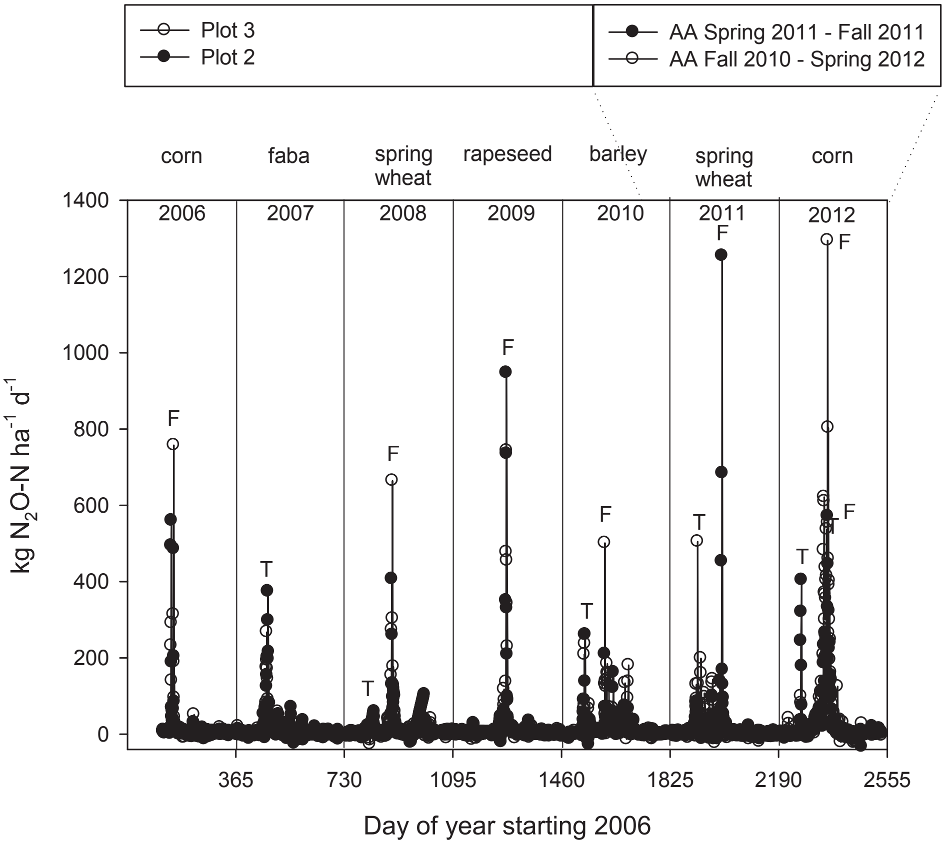

Figure 1. Fall vs. Spring: N_2O emissions from the TGAS-MAN study site from 2006 through 2012. Emission episodes due to fertilizer applications (F) and spring thaw (T) emissions are shown. Also shown are fall 2010, spring 2011, fall 2011, and spring 2012 anhydrous ammonia emissions.

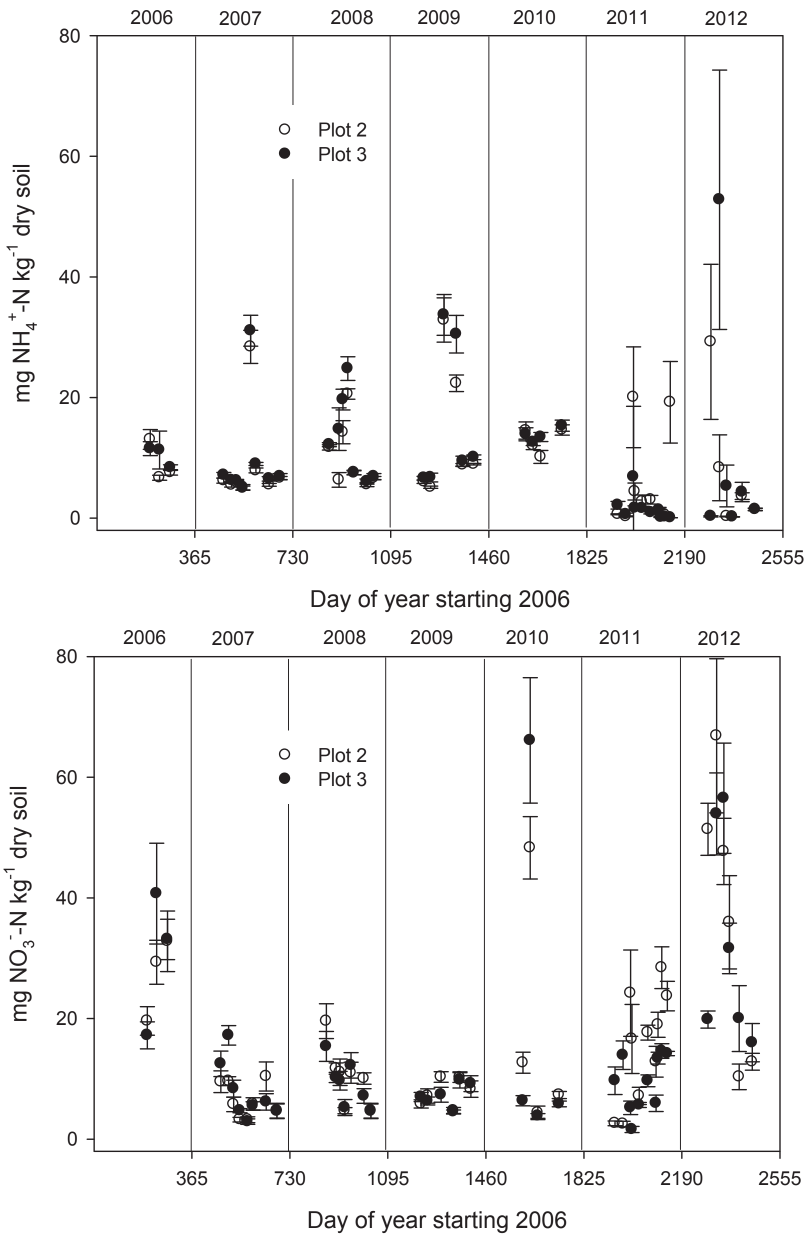

Figure 2. Fall vs. Spring: Extractable NH_4^+ and NO_3^- from soil for Plot 2 and 3 at the TGAS-MAN study site.

Table 2. Fall vs. Spring: Grain and total aboveground biomass yield for the TGAS MAN study.

Treatment	Grain Yield	Total Aboveground Biomass
2011	Mg dry mass ha^{-1}	Mg dry mass ha^{-1}
Spring (Plot 2)	1256 (125)	1676 (214)
Fall (Plot 3)	556 (126)	732 (157)
2012		
Fall (Plot 2)	6767 (242)	12100 (428)
Spring (Plot 3)	6686 (878)	11934 (1167)

Table 3. Fall vs. Spring: N_2O cumulative ($\sum F_N$), maximum (maxF_N), cumulative fall through spring ($\sum F_N$ F-S), and maximum fall through spring (maxF_N F-S) emissions over the 2010/11 and 2011/2012 study years for fall and spring applied anhydrous ammonia (AA) at the TGAS-MAN study site.

	Spring AA F_N (kg N ha^{-1} d^{-1})				Fall AA F_N (kg N ha^{-1} d^{-1})			
	$\sum F_N$	maxF_N	$\sum F_N$ F-S	maxF_N F-S	$\sum F_N$	maxF_N	$\sum F_N$ F-S	maxF_N F-S
2010/11	5057	1254	1048	86	3154	505	2472	505
2011/12	14101	1294	406	100	9353	572	1615	405

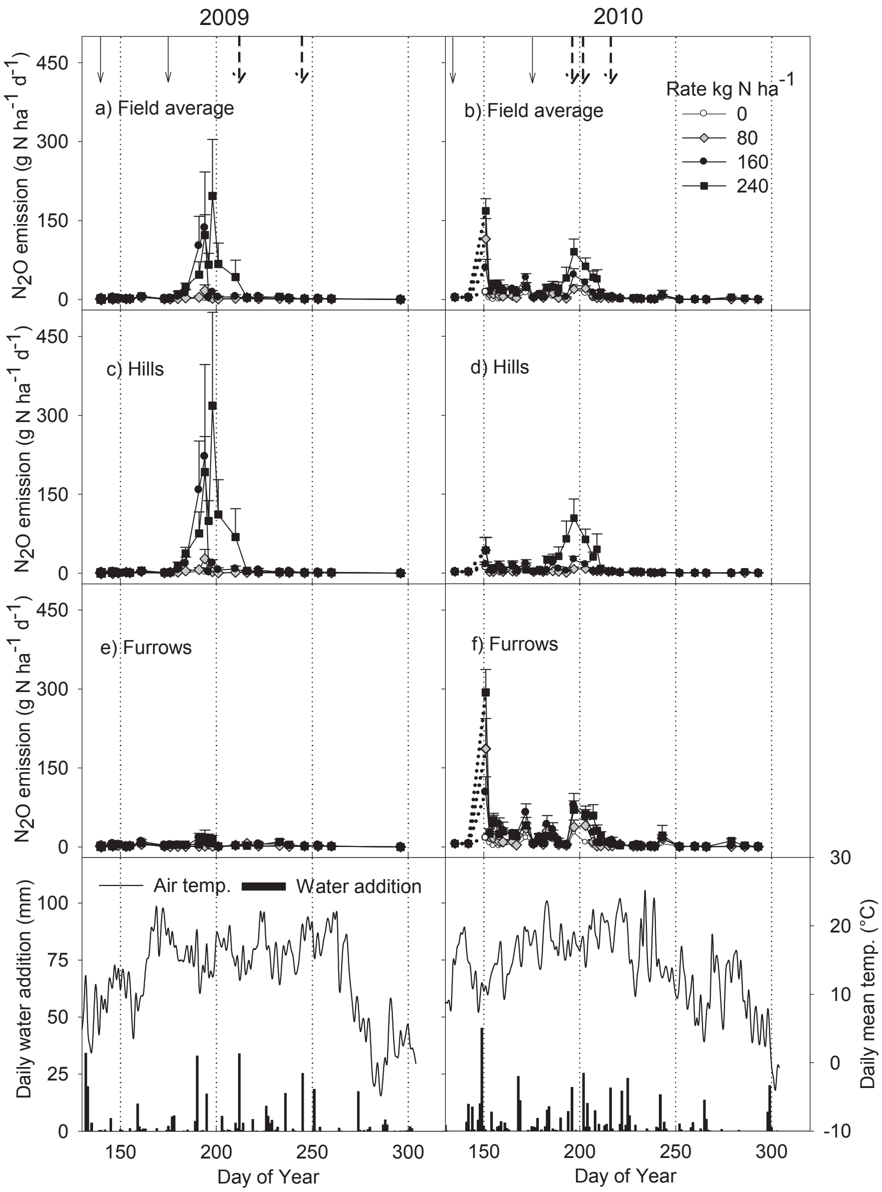

Figure 3. N Rate: Mean daily N_2O emissions estimated for treatment plots [average (a, b)], and within plot components, hills (c, d), and furrows (e, f) as affected by fertilizer N rate. Also shown are the average daily air temperature (solid line) and daily water addition (bars, precipitation + irrigation) during the crop seasons in 2009 and 2010. Dotted lines in 2010 indicate the linear interpolation between planting (DOY 135) and the first sampling date (DOY 151). Bars indicate +1 standard error (n = 8) of the mean. The downward solid and dash arrows indicate timing of urea fertilizer additions, and irrigation additions, respectively.

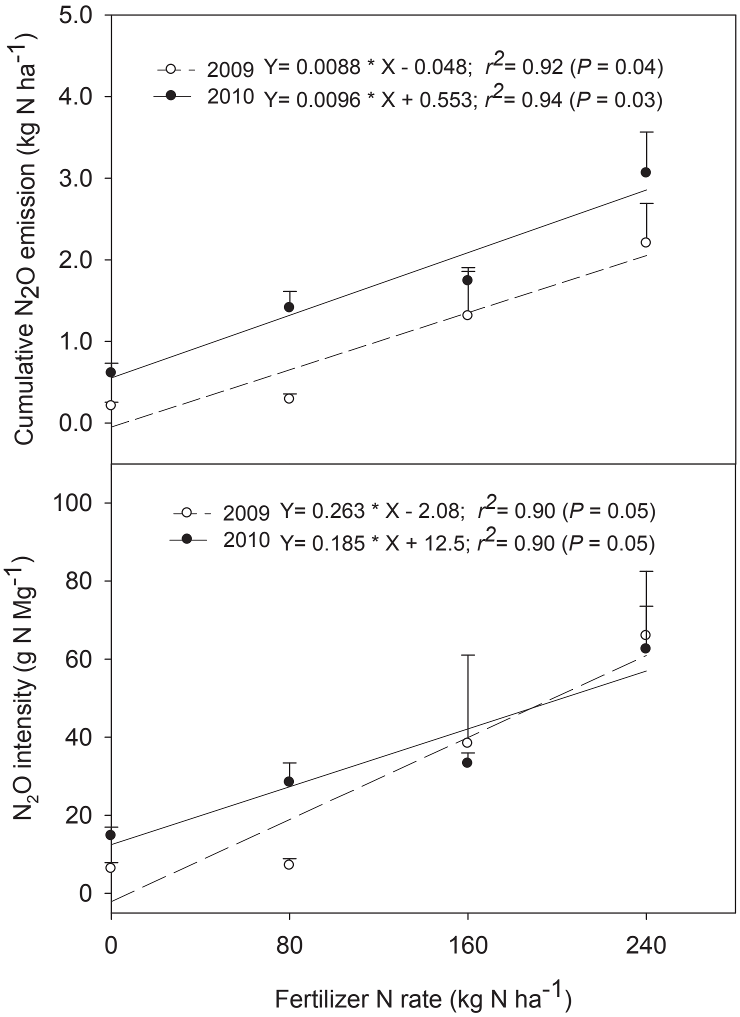

Figure 4. N Rate: Growing season cumulative N_2O emissions and yield based N_2O intensity as a function of fertilizer N rate in 2009 and 2010. Bars indicate +1 standard error (n = 8 for cumulative N_2O emission and n = 4 for N_2O intensity) of the mean.

Table 4. N Rate: Growing season cumulative N_2O emissions and fertilizer-induced emission factor [EF_{gs}] 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	Cumulative N_2O emissions			EF_{gs}		
(kg ha^{-1})	2009	2010	Avg.	2009	2010	Avg.
	------------- (kg N_2O-N ha^{-1}) --------- -			------------------ (%)----------------------		
0	0.21 c*	0.61 c	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	$Pr \geq$ F		df	$Pr \geq$ F	
N rate	3	<0.001		2	0.262	
Year	1	<0.001		1	0.004	
N × Year	3	0.022		2	0.119	

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

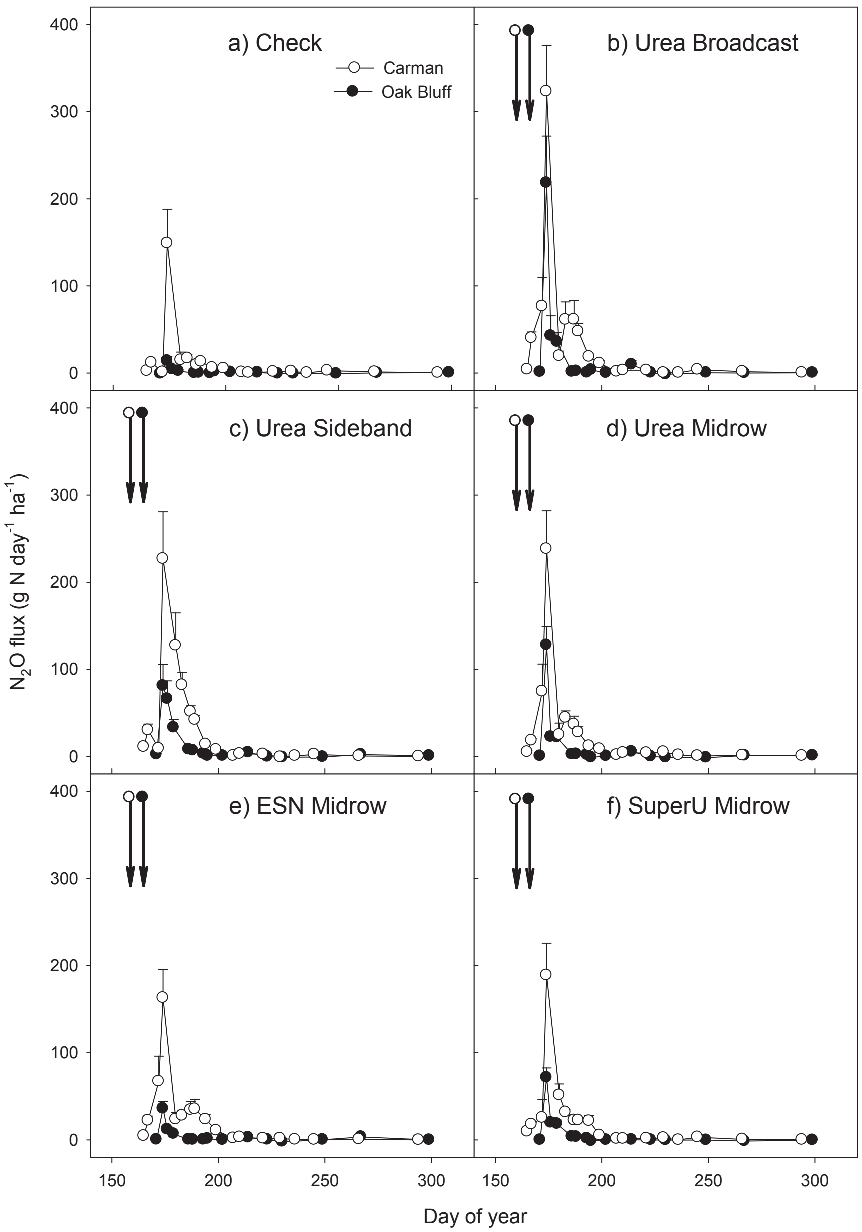

Figure 5. Red River Placement: Nitrous oxide fluxes from a) Check, b) midrow applied polymer coated urea (ESN), c) broadcasted Urea, d) mid-row applied inhibitor mixed with urea (SuperU), e) side banded Urea and f) mid-row applied Urea at the rate of 80 kg available N ha^{-1} in 2011 at Oak Bluff and Carman. Bar indicate +1 standard error of the means, n = 16. The downward arrows indicate application of N fertilizers.

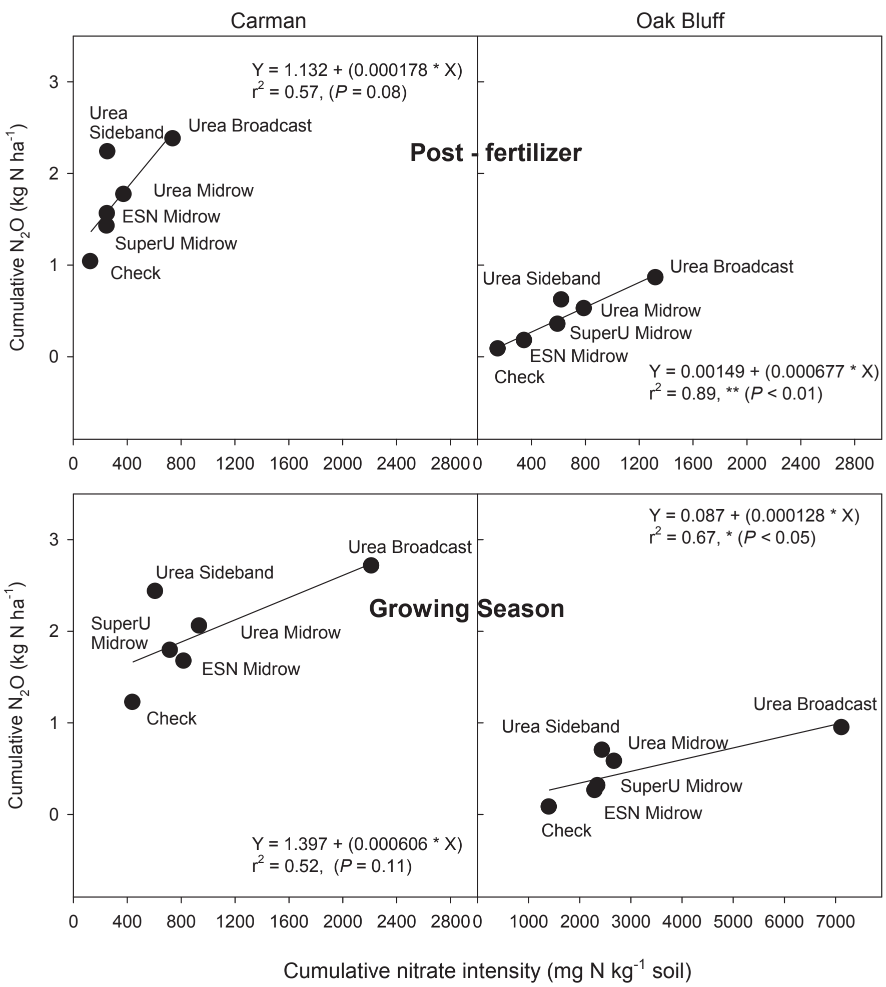

Figure 6. Red River Placement: The relationship between cumulative N_2O-N emission and nitrate intensity during the post N application and growing season periods at Oak Bluff and Carman in 2011. Nitrate intensity is calculated as a summation of mean daily soil nitrate concentration at 0–15 cm.

Table 5. Red River Placement: Cumulative N_2O-N emissions and emission factors (EF) from Check and mid row banded polymer coated urea (ESN Midrow), inhibitors mixed with urea (SuperU Midrow) and Urea (Urea Midrow) and broadcasted (Urea Broadcast) and side banded (Urea Sideband) Urea in 2011 at Carman and Oak Bluff, Manitoba. Means are compared using the LSD at *α* = 0.05 probability.

Treatment	Cumulative	EF[¥]	EF N surplus[β]	EF - emission intensity[ä]
	- (kg N_2O-N ha^{-1}) -	------ (%) ------		------ (kg N t^{-1}) ------
Check	0.65d			0.21d
Urea Broadcast	1.83a	1.47a	-76	0.52a
Urea Sideband	1.55ab	1.13ab	-108	0.46ab
Urea Midrow	1.32b	0.83bc	-138	0.37abc
ESN Midrow	0.96c	0.39c	-1099	0.28cd
SuperU Midrow	1.04c	0.50c	-1910	0.27cd
Site				
Carman	1.97	1.13	-841	0.55
Oak Bluff	0.48	0.60	-491	0.15
P value				
Treatment	< 0.001	< 0.001	ns	< 0.001
Site	< 0.001	< 0.001	ns	< 0.001
Treatment * Site	ns	ns	ns	ns
n	16	16	4	4

Note. EF[¥] is increase in N_2O-N emissions over the control as percentage of N applied. EF N surplus[β] is calculated as N applied minus N uptake divided by N_2O-N emissions over the control. EF emission intensity[ä] is the ratio of cumulative N_2O-N emission to grain yield.

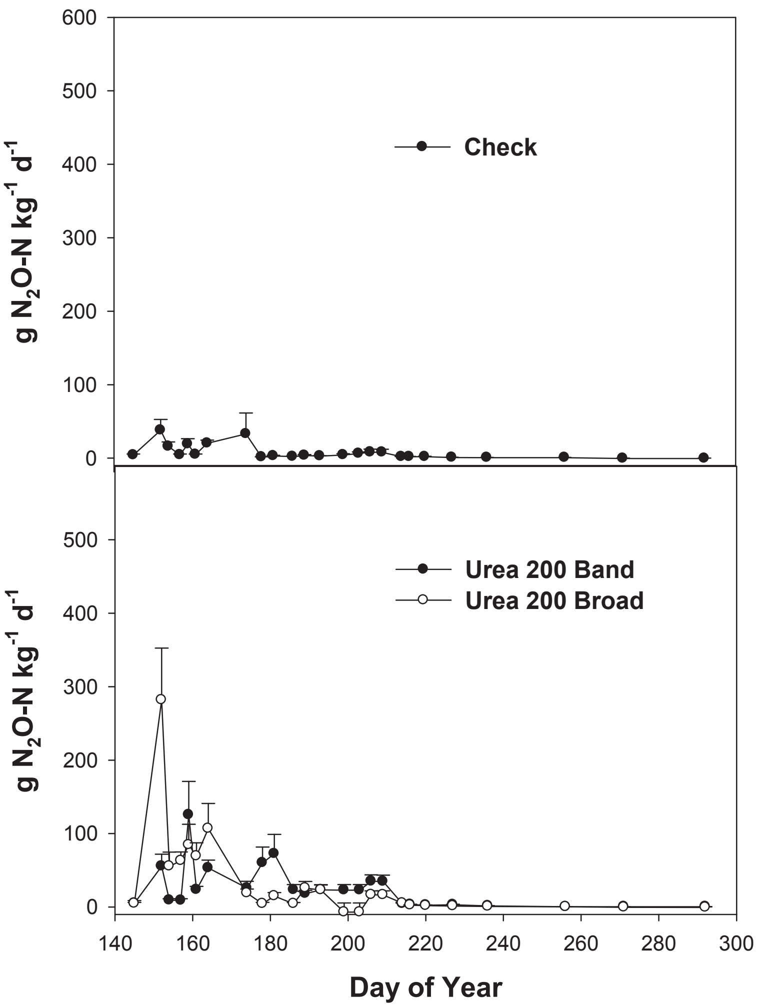

Figure 7. Potato Placement: Emission of nitrous oxide in 2011 from the AESB-Carberry N Placement Study planted to Russet Burbank under irrigation. Treatments shown are, Check (0 kg N ha^{-1}), and Urea 200 Broad and Urea 200 Band as 200 kg N ha^{-1} broadcast incorporated following application at hilling and single application banded to the side of seed tubers, respectively. Means are for 16 chamber locations for each treatment ± 1 standard error of the mean.

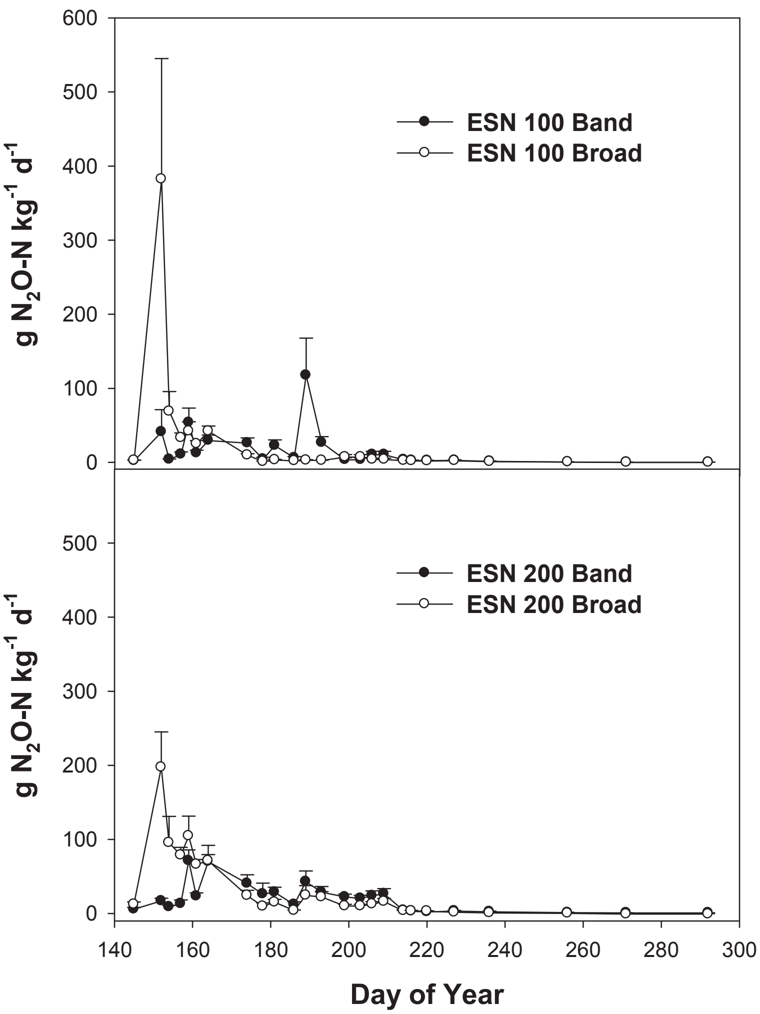

Figure 8. Potato Placement: Emission of nitrous oxide in 2011 from the AESB-Carberry N Placement Study planted to Russet Burbank under irrigation. Treatments shown are, ESN 100 Broad and ESN 100 Band as 100 kg N ha^{-1} broadcast incorporated following application at hilling and single application banded to the side of seed tubers, respectively, as well as ESN 200 Broad and ESN 200 Band as 200 kg N ha^{-1} broadcast incorporated following application at hilling and single application banded to the side of seed tubers, respectively. Means are for 16 chamber locations for each treatment ± 1 standard error of the mean.

Table 6. Potato Placement: Cumulative nitrous oxide emissions and emission factors in 2011 from plots of the AESB-Carberry N Placement Study study planted to Russet Burbank under irrigation. Emission factors for each rate of N addition were calculated as emissions above the 0 N rate divided by added N. Values in a column followed by a different letter are different ($P < 0.05$).

Treatment	Rate	Placement	Cumulative Emission	Emission Factor
	kg N ha^{-1}		kg N ha^{-1}	%
Check	0		1.02 c	-
ESN	100	Broadcast	3.64 ab	2.62
ESN	200	Broadcast	4.54a	1.76
Urea	200	Broadcast	4.43 a	1.71
ESN	100	Sideband	2.36 b	1.34
ESN	200	Sideband	2.89 b	0.94
Urea	200	Sideband	3.66 ab	1.32

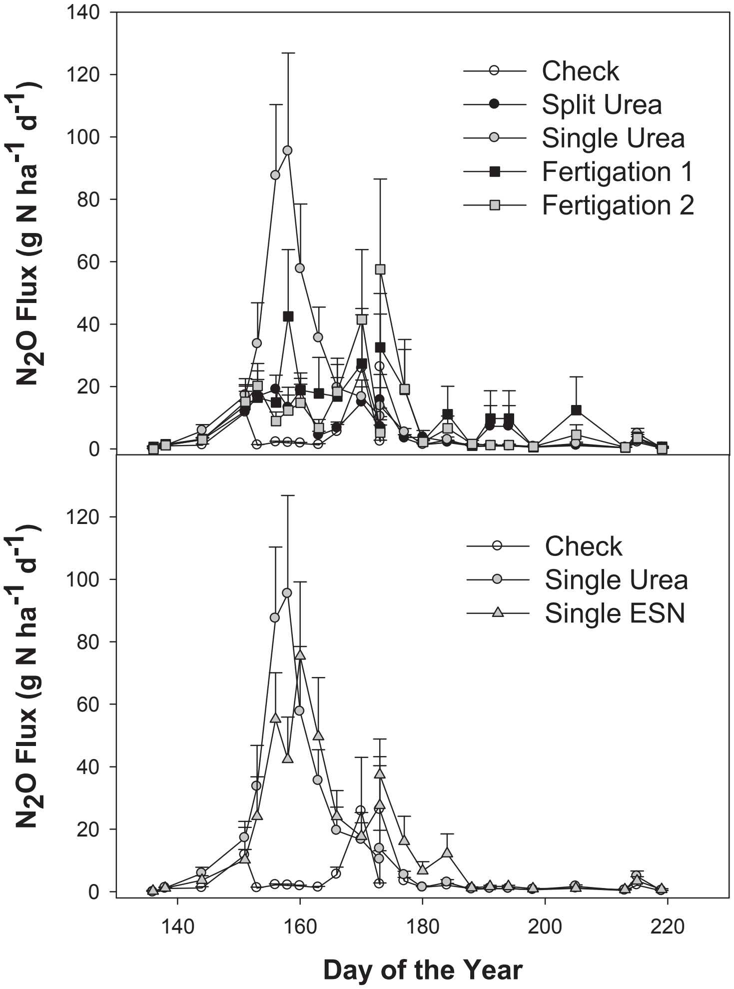

Figure 9. N Strategy: Emission of nitrous oxide in 2011 from select treatments of the Nitrogen Management in Irrigated Potato Systems study with Russet Burbank under irrigation. Note the Single Urea treatment is shown again at bottom for purpose of comparison to the Single ESN treatment. Means are for 16 chamber locations for each treatment ± 1 standard error of the mean.

Table 7. N Strategy: Cumulative nitrous oxide emissions in 2011 from select treatments of the Nitrogen Management in Irrigated Potato Systems study with Russet Burbank under irrigation. The cumulative emissions and the estimated emission factor are shown. Emission factors for each rate of N addition were calculated as emissions above the 0 N rate divided by added N. Values in a column followed by a different letter are different (P < 0.05).

Treatment	Cumulative Emission	Emission Factor
	kg N ha^{-1}	%
Check	0.34 c	-
Split Urea	0.56 b	0.13
Single Urea	1.47 ab	0.63
Single ESN	1.46 ab	0.62
Fertigation 1	1.02 b	0.38
Fertigation 2	0.88 b	0.30

Table 8. Summary of results for impact of 4R practices on N_2O emissions in the studies conducted in this project. Site years to be completed because gas, soil and plant samples were collected after the project close (July 2012) are given in parentheses.

Objective	Trial Name	Site Years	Results	Follow up
Fall vs. Spring	TGAS MAN	2	36% reduction in emissions with late fall than spring application	Examine if inhibitors can further reduce emissions from late fall application
N Rate	Potato N Rate	2	Emissions increased linearly with rate and not related to yield	none
Placement	Red River Placement	2(2)	Banding reduced emissions (side 24%, mid 43%) with ESN and SuperU mid-banded most reducing emissions (74%) to broadcast incorporation	Complete analysis (>July 2012) for 2 sites
Placement	Potato Placement	1(1)	Reductions: 24% banding urea, 47% banding ESN. ESN broadcast incorporated no effect	Complete analysis (>July 2012) for 1 site
Placement	Potato N Strategy	1(1)	Conventional split urea lower emissions than single or fertigation treatments	Complete analysis (>July 2012) for 1 site

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

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Gao, X., Tenuta, M., Nelson, A., Sparling, B., Tomasiewicz, D., Mohr, R. M. and Bizimungu, B. 2013. **Effect of nitrogen fertilizer rate on nitrous oxide emission from irrigated potato on a clay loam soil in Manitoba, Canada**. Can. J. Soil Sci. **93**: xxx–xxx. This study examined the effect of N fertilizer application rate on N_2O emissions for irrigated potato production on a clay loam soil near Carberry, Manitoba, over two growing seasons. Treatments were an unfertilized control, and urea-N fertilizer application rates of 80, 160 and 240 kg N ha^{-1}, which were applied as split applications. The marketable yield increased at 80 kg N ha^{-1} relative to the unfertilized control, but did not respond to higher rates of fertilizer. Peak emission of N_2O followed fertilizer application and rain or irrigation events. Emission rates following fertilizer application and water addition events were greater from hill than from furrow position in 2009, but not in 2010. In the latter, ponding of water in furrows likely resulted in the greater emissions than from the hill positions. Cumulative N_2O emissions and yield based N_2O intensity increased linearly with N application rate. The growing season emission factor (EF_{gs}) for percent of added N emitted as N_2O was 0.73% and did not increase with N application rate. The adjusted whole-year emission factor (EF_{wy}) assuming 30% of annual emissions are emitted during winter and thaw was 1.04%, being lower than the Canadian IPCC Tier II protocol value of 1.72% for irrigated cropland in Canada. The lower measured EF_{wy} may be because the protocol assumes that under irrigation water input (rain plus irrigation) equals potential evapotranspiration (PET) from May to October, implying no restriction of N_2O emissions by water limitation. For the current study, however, the ratio of water input to PET averaged 70%, suggesting water may have restricted N_2O emission, therefore resulting in a lower EF_{wy} than predicted by the Tier II protocol. The results of the current study also suggest that a reduction in N_2O emissions can be achieved by avoiding fertilizer N applications beyond optimal for marketable yield, limiting irrigation soon after application of N fertilizer, and managing irrigation to prevent ponding of water in furrows.

Key words: Canadian prairies, clay loam soil, emission factor, irrigation, moisture, precipitation

Gao, X., Tenuta, M., Nelson, A., Sparling, B., Tomasiewicz, D., Mohr, R. M. et Bizimungu, B. 2013. **Incidence du taux d'application des engrais sur les émissions d'oxyde nitreux dans les champs de pomme de terre irrigués sur loam argileux au Manitoba (Canada)**. Can. J. Soil Sci. **93**: xxx–xxx. Cette étude s'est intéressée à l'incidence du taux d'application des engrais N sur la quantité de N_2O émise par les cultures de pomme de terre irriguées, sur un loam argileux près de Carberry, au Manitoba, pendant deux périodes végétatives. Les traitements consistaient en une parcelle témoin non bonifiée et en l'application d'urée à raison de 80, 160 ou 240 kg de N par hectare (application fractionnée). L'application de 80 kg de N par hectare augmente le rendement en tubercules commercialisables comparativement à celui de la parcelle témoin non fertilisée, mais le rendement ne réagit pas aux taux d'application plus élevés. Les dégagements de N_2O atteignent un maximum après l'application d'engrais et une pluie ou l'irrigation. La quantité d'émissions après l'application d'engrais et l'addition d'eau était plus importante sur les buttes que dans les sillons en 2009, mais ce n'était pas le cas en 2010. L'accumulation d'eau dans les sillons explique sans doute les émissions plus importantes que sur les buttes la deuxième année. Les dégagements cumulatifs de N_2O et l'intensité des émissions de N_2O établie en fonction du rendement augmentent de façon linéaire avec le taux d'application des engrais N. Le coefficient d'émissions pendant la période végétative (EF_{gs}) de la partie des engrais N qui se transforme en N_2O était de 0,73 % et n'augmente pas avec le taux d'application des engrais. Le coefficient d'émissions ajusté pour l'année entière (EF_{wy}), en supposant que 30 % des dégagements annuels surviennent en hiver et au dégel, s'élevait à 1,04 %, ce qui est inférieur à la valeur de 1,72 % établie pour les terres irriguées du Canada par le protocole de niveau deux du GIEC canadien. La valeur plus faible de EF_{wy} obtenue lors des relevés pourrait s'expliquer par la supposition, faite dans le protocole, que l'apport d'eau quand il y a

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Abbreviations: **DOY**, day of the year; **PET**, potential evapotranspiration

irrigation (précipitations plus irrigation) équivaut au potentiel d'évapotranspiration (PET) de mai à octobre, ce qui laisse croire que la limitation d'eau ne restreint en aucune manière les dégagements de N_2O. Dans le cadre de cette étude cependant, le ratio entre l'apport d'eau et le PET se situait en moyenne à 70 %, signe que l'eau pourrait avoir effectivement limité les émissions de N_2O, ce qui aurait donné un EF_{wy} inférieur à celui prévu par le protocole du deuxième niveau. Les résultats de cette étude suggèrent aussi qu'on pourrait réduire les émissions de N_2O en évitant d'appliquer des engrais N au-delà du taux donnant un rendement optimal en tubercules commercialisables, en réduisant l'irrigation peu après l'application d'engrais N et en gérant l'irrigation pour que l'eau ne s'accumule pas dans les sillons.

Mots clés: Prairies canadiennes, loam argileux, coefficient d'émissions, irrigation, humidité, précipitations

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 major contributors 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 greenhouse gas 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 O_2 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 (Agriculture and Agri-Food Canada 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-yr 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}). The Tier II EF_{reg} and EF_{irri} were derived from a limited number of studies and none from Manitoba in the Black Soil zone. An ideal national inventory on estimation of N_2O emission should, however, include numerous studies in the soil and climate zones of the Canadian prairies. Further, N_2O emissions can vary with crop (Kaiser et al. 1998). Specifically, in studies comparing N_2O emissions from fields cropped with potato (*Solanum tuberosum* L.) and other crops, N_2O emissions per unit N applied were generally higher from the potato field than from other cropped fields (Smith et al. 1998; Ruser et al. 2001). These studies highlight the importance of crop-specific field management in affecting N_2O emissions from agricultural soils.

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). A number of studies have examined N_2O emissions in potato fields as affected by N fertilizer management (Smith et al. 1998; Ruser et al. 2001; Vallejo et al. 2006; Haile-Mariam et al. 2008; Buchkina et al. 2010). In a non-irrigated potato field in New Brunswick, fertilizer N application at 200 kg N ha^{-1} significantly increased cumulative N_2O emissions over an unfertilized control. Additionally, split application of fertilizer resulted in lower emissions than a single application at planting (Burton et al. 2008b). In other field studies in Minnesota with irrigated potato, application of polymer-coated urea prior to planting resulted in significantly lower N_2O emission than the typical split application of urea and NH_4NO_3, without increasing growing season nitrate leaching (Hyatt et al. 2010; Venterea et al. 2011). Those studies provided valuable information on the fertilizer application strategies to improve fertilizer use efficiency and reduce N_2O emission. To our knowledge, however, there are no studies examining N_2O emissions for potato production on the Canadian prairies, which accounts for 38% of the total potato production area in Canada, with the majority in Manitoba (Statistics Canada 2011). Site-specific estimates of direct emissions should consider the variations in climate, soil moisture and temperature conditions, mineral N concentration and management practices (Beauchamp 1997). Differences in these parameters reduce the applicability of emission rates from other regions (e.g., Burton et al. 2008b) to the prairie potato systems. Manitoba has the second largest potato production acreage among Canadian provinces, with an estimated 30 000 ha in 2011 (Statistics Canada 2011). In contrast to production practices in Atlantic Canada, where N fertilizers are banded and no irrigation is used, 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. In this sense, this study aimed to fill a gap in understanding of the contribution of irrigated potato production in the national inventory of N_2O emissions and therefore improve the Tier II approach for Canada.

MATERIALS AND METHODS

Site Description and Experimental Design

This study was part of a 3-yr (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 (CMCDC) (lat. 49°54′N, long. 99°21′W) in Carberry, Manitoba. The existing field experiments in 2009 and 2010 were used in the current study. Monitoring of N_2O emissions was conducted in plots (3.8 m × 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.

The soil at the experimental sites is a clay loam (sand 32%, silt 40%, and clay 28%) soil in the Wellwood series being classified as an Orthic Black Chernozem (Mills and Haluschak 1995). Initial characteristics of the surface (0–15 cm) soil in the fall prior to each planting were pH (H_2O) 5.9 and 6.2, organic carbon 37.2 and 31.4 g kg^{-1}, NO_3^--N 14.7 and 11.5 mg kg^{-1}, and $NaHCO_3$-extractable P 25 and 13 mg kg^{-1}, for the 2009 and 2010 sites, respectively. In keeping with soil testing recommendations, soil samples were collected from different plots and combined into one sample for determination of characteristics (Manitoba Soil Fertility Guide 2004). Soil texture was determined by the pipette method (Loveland and Walley 1991). Air-dried and sieved (2 mm) soil samples were extracted using 0.5 M $NaHCO_3$, with NO_3^--N concentration in the extract measured colorimetrically with an auto analyzer (Oakland, CA), and P with an ARL 3410 inductively-coupled plasma unit (Sunland, CA). Total organic carbon was determined by wet oxidation (Tiessen and Moir 1993).

The experimental design was a randomized complete block with four replicates. Fertilizer N treatments included an unfertilized check (Control) and application rates of 80, 160, and 240 kg N ha^{-1} as broadcast-incorporated urea, which was applied as a split application with 50% just prior to planting and 50% at hilling. Row and seed piece spacing was 0.95 m and 0.38 m, respectively. Other agronomic management followed practices appropriate for the local area potato production. Irrigation water from a groundwater source was applied by sprinkler based on monitoring the soil moisture level using tensiometers. Approximately 20–25 mm irrigations were performed for each application when the soil water content was below 65% available water capacity. Blanket applications of triple super phosphate (0–45–0) of 142 and 185 kg ha^{-1} and KCl (0–0–60) of 86 and 93 kg ha^{-1}, respectively, in 2009 and 2010, were broadcast and incorporated prior to planting to meet crop needs. In 2010, potassium-magnesium-sulphate (22% K_2O, 11% Mg and 22% S) was also applied at 49 kg ha^{-1}. Application rates were based on a combination of provincial recommendations and knowledge of the site (Manitoba Soil Fertility Guide 2004). Pesticides were applied as required to effectively control weeds, insect, and fungal diseases, using recommended pesticides and rates (Manitoba Agriculture, Food and Rural Initiatives 2009).

Planting occurred on 2009 May 20 [day of year (DOY) 140] and 2010 May 15 (DOY 135) using a Cheechi e Magli two-row planter (Budrio, IT). Hilling occurred on 2009 Jun. 24 (DOY 175) and 2010 Jun. 23 (DOY 174), using a Grimme two-row rotary power hiller and a Lilliston two-row disc bedder (Bigham Brothers Inc., Lubbock, TX), respectively. Harvest occurred on 2009 Sep. 18 (DOY 261) and 2010 Sep. 28 (DOY 271) using a Grimme two-row harvester (Grimme GmbH and Co. KG, Damme, DE). A flail mower was used to chop the vines prior to harvest. Average marketable tuber yield (>85 g) was 33, 41, 38 and 35 Mg ha^{-1} in 2009 and 41, 50, 52, and 49 Mg ha^{-1} in 2010 for the 0, 80, 160, and 240 kg N ha^{-1} fertilizer rates (Mohr et al. 2009, 2010). Yields were higher in 2010 than 2009 and were typical of the local commercial production.

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 2 to 6 wk 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.

Sampling for N_2O emissions was performed between May 26 and Oct. 23 (DOY 146–296) in 2009 and between May 31 and Oct. 20 (DOY 151–293) in 2010, respectively. The time interval between samplings was mostly 3–7 d in 2009 and 2–3 d in 2010. The interval was occasionally increased to 11–12 d for samplings on DOY 173 and DOY 233 in 2009, and on DOY 279 in 2010. In 2009, only one measurement after harvest was taken on DOY 296. Determination of sampling date was dependent on the weather conditions and farming activities. The N_2O emission sampling was conducted using vented, two-piece (collar and lid), polyvinyl chloride (PVC) static cylindrical chambers (Tenuta et al. 2010). The collars measured 20.3 cm internal diameter by 10 cm high. Lids covered with reflective aluminum foil were 0.6 cm thick with a diameter of 23 cm. Two collars were installed at approximately 3 cm depth on hill and furrow position for each plot. Collars on hill positions were placed between plants. The collars were installed a day prior to the first sampling and were covered only during gas sampling. The collars were installed permanently and only removed and re-installed for hilling. For sampling, lids were attached to the collars and 20-mL gas samples were collected through a rubber septum at regular intervals (0, 20, 40 and 60 min) using syringes (Becton-Dickinson, Franklin Lakes, NJ) and subsequently transferred to 12-mL thrice helium-flushed pre-evacuated to 0.04 mPa glass vials (Labco Exetainer, High Wycombe, UK). A layer of all-purpose Silicon II was used on the top to seal the vials. Two 20-millilitre standard gas mixtures (N_2O, CH_4 and CO_2) were also injected into pre-evacuated vials prior to going to the field site, and handled in the same manner as other gas samples to confirm sample integrity during sampling and storage. All vials were transported back to the laboratory for analysis.

Concentrations of N_2O in gas samples were determined by gas chromatography using a Varian CP–3800 gas chromatograph equipped with electron capture detector and a Combi-Pal auto sampler system. Analysis of a sample set was either repeated or the gas chromatograph column reconditioned and calibration redone if quality control samples were off by more than 5% of the expected concentration. The 60-min deployment time resulted in repression of N_2O accumulation with time for chamber locations of very active emissions. The N_2O emission rates (ng N_2O-N m^{-2} min^{-1}) were calculated using the HMR package (Pedersen 2011) implemented with the R language. The package recommends application of one of three regression approaches to estimate emission from the accumulation of N_2O during chamber deployment. A non-linear model (Hutchinson and Mosier 1993) is recommended if the accumulation of N_2O decreased with time. A linear model is recommended if the accumulation or dissipation of N_2O was consistent with time. An emission of zero is recommended in the absence of a clear trend in gas concentration with time. In this study we did not remove outlier concentration data from emission estimations or force negative emissions to zero. The application of the HMR package resulted in 19.7% of emissions estimated using a non-linear model, 79.2% a linear model, and 1.1% of the emission estimates forced to zero.

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. In 2009, the period was filled by linear interpolation assuming daily emission rate at planting (DOY 140) to be the averaged value over the first 2 wk of measurements in the Control treatment. In 2010, the first sampling on DOY 151 had emissions for N_2O in response to fertilizer additions on DOY 134 and 12 mm rainfall occurred on DOY 142, hence emissions were gap-filled separately for the periods prior to and after the rain. The emission rate from planting (DOY 135) until rainfall (DOY 142) used to fill gaps in measurements was taken as the average of emissions for the first 2 wk of measurements obtained for the Control treatment. Emissions for the period from the rainfall to the first measurement were obtained by linear interpolation. Cumulative emission for a chamber (ng N_2O-N m^{-2}) location were up-scaled to the field scale (kg N_2O-N ha^{-1}) assuming that 50% hills/50% furrows covered the plot area before final hilling and 60% hills/40% furrows afterwards.

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. Means were compared with Fisher's least significant differences (LSD) test. Pearson correlation analysis for selected factors was conducted using PROC CORR. In all cases, differences among treatments were declared to be significant at $\alpha < 0.05$. Prior to analyses, data were tested for homogeneity of residuals using the Kolmogorov–Smirnov test and, as a result, the cumulative N_2O emissions data were subject to log-transformation (base 10). Treatment means and standard errors calculated from untransformed data are presented in tables and figures.

RESULTS

Climate

Average air temperature May through October in both 2009 and 2010 was 13°C, being similar to the long-term normal (Table 1). Total rainfall plus irrigation May through October was 344 mm 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 with 2009. Thus, the growing season of 2010 had greater water input than that of 2009 due to a combination of greater precipitation and irrigation. Accordingly, standing water was noted in the furrows at times in 2010, especially following a heavy rainfall on DOY 149 and during the frequent water additions between late July and early August (DOY 194–226).

Table 1. Mean monthly air temperature, water additions by precipitation and irrigation for the 2009 and 2010 study period in comparison to the long-term (1991–2010) normal

	May	Jun.	Jul.	Aug.	Sep.	Oct.	May–Oct.
Mean temperature (°C)							
2009	9	15	16	16	17	2	13
2010	10	15	18	18	11	7	13
Water additions (mm)							
2009 precipitation	68	35	77	56	22	36	294
2009 irrigation	0	0	25	0	25	0	50
2010 precipitation	127	72	67	84	35	31	416
2010 irrigation	0	0	45	19	0	0	64
Normal (1991–2010)							
Mean temperature (°C)	10	16	18	17	13	5	13
Precipitation (mm)	73	81	65	53	39	33	344

Mean Daily N_2O Emissions

Daily N_2O emission rate within sample positions was highly variable with the coefficients of variation (CV) in 2009 and 2010 ranging from 77 to 402% and from 73 to 438%, respectively. In 2010, but not in 2009, N_2O emission increased 2 wk after fertilizer application, coinciding with the greatest rainfall event (45 mm, DOY 149; Fig. 1). In both years, fertilizer N addition at hilling was followed by an increase in N_2O emission, which reached a maximum approximately 20 d in 2009 and 25 d 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. For example, in 2009, the maximum emission rate occurred on DOY 198, coinciding with the rainfall of 33 mm on DOY 190, which was also one of the largest water addition events in that year. In 2010, the maximum emission rate was recorded on DOY 151, coinciding with the 45 mm rainfall on DOY 149 in that year. Also, the second highest emission rate in 2010 occurred on DOY 197, coinciding with the water additions by irrigation of 19 mm on DOY 196.

In 2009, an N_2O emission episode occurred after fertilizer applications and water addition events (DOY 176–216) for the hill but not for the furrow position (Fig. 1c, e). In 2010, however, N_2O emission episodes occurred after fertilizer applications and water addition events (DOY 140–161, DOY 180–216) for both hill and furrow positions. The emission episode following fertilizer application before planting was much more evident in the furrow than in the hill position, though because of the gap between sampling times it cannot be certain that emission may have already occurred and subdued for the hill positions.

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 2). 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.

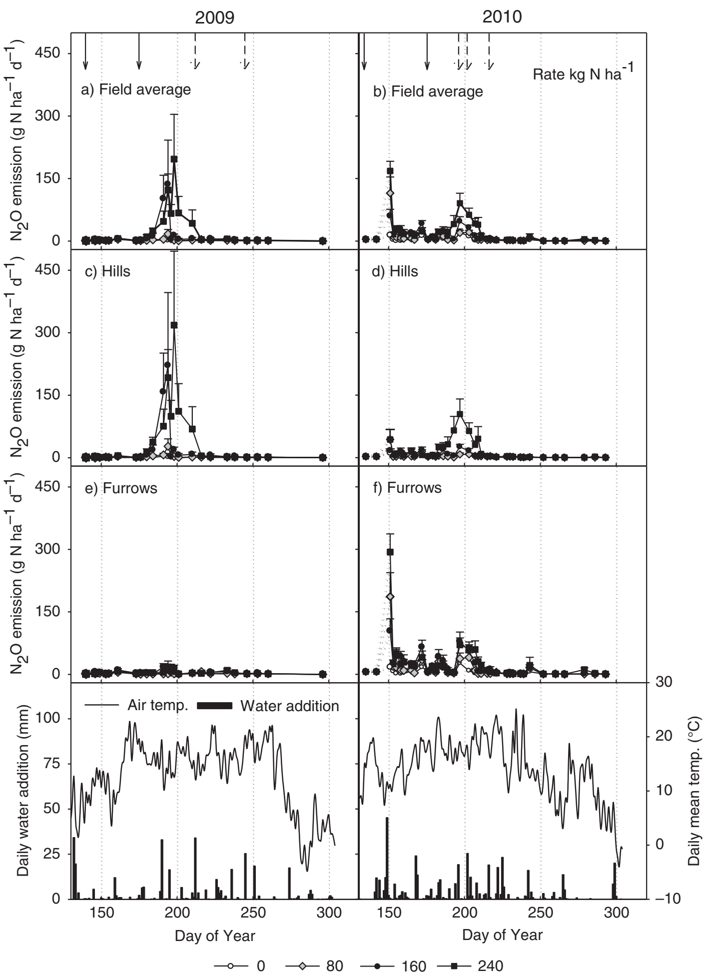

Fig. 1. Mean daily N_2O emissions estimated for treatment plots [average (a, b)], and within-plot components, hills (c, d), and furrows (e, f) as affected by fertilizer N rate. Also shown are the average daily air temperature (solid line) and daily water addition (bars, precipitation + irrigation) during the crop seasons in 2009 and 2010. Dotted lines in 2010 indicate the linear interpolation between planting (DOY 135) and the first sampling date (DOY 151). Bars indicate + 1 standard error (n = 8) of the mean. The downward solid and dash arrows indicate timing of urea fertilizer additions, and irrigation additions, respectively.

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 6 wk 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. 2). The increase in N_2O emissions per unit applied N fertilizer was slightly higher in 2010 than in 2009 likely resulting in the fertilizer rate and year interaction (Table 2). Similar to cumulative emissions, the yield-based N_2O intensity also increased linearly with fertilizer rate each year (Fig. 2).

The calculated EF_{gs} ranged from 0.10 to 1.02%, with an overall average value of 0.73% (Table 2). 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.

Table 2. Growing season cumulative N_2O emissions and fertilizer-induced emission factor [EF_{gs}] 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 2009	2010	Avg.	EF_{gs} 2009	2010	Avg.
	(kg N_2O-N ha^{-1})			(%)		
0	0.21*c*	0.61*c*	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* ≥ F		df	*Pr* ≥ F	
N rate	3	< 0.001		2	0.262	
Year	1	< 0.001		1	0.004	
N × Year	3	0.022		2	0.119	

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

DISCUSSION

To our knowledge, this is the first study to investigate the effect of N fertilizer rate on N_2O emissions in irrigated potato in the Canadian prairies. Thus, this study of N_2O emissions can help to quantify the contribution of irrigated potato production and fill a gap in the national inventory of N_2O emissions from agricultural soils in western Canada. 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.

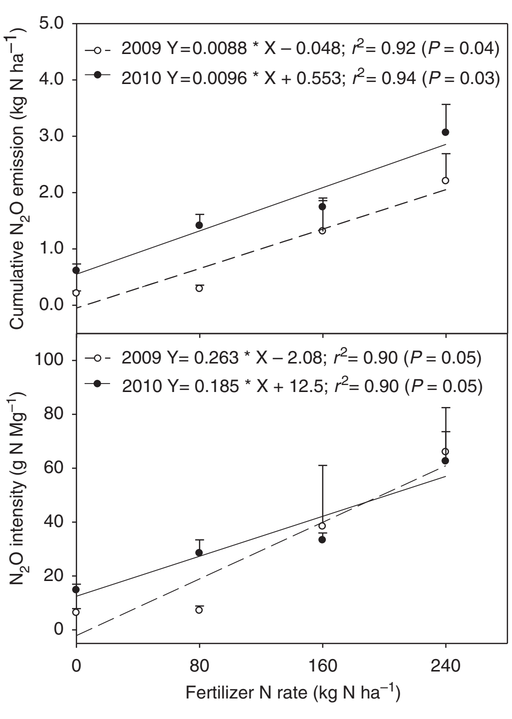

Fig. 2. Growing season cumulative N_2O emissions and yield based N_2O intensity as a function of fertilizer N rate in 2009 and 2010. Bars indicate + 1 standard error ($n = 8$ for cumulative N_2O emission and $n = 4$ for N_2O intensity) of the mean.

Both cumulative emission of N_2O and yield based N_2O intensity increased linearly with fertilizer rate, 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 for 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. Of course, the optimum N rate for potato production will vary greatly with the soil, crop and environmental conditions. The other potato cultivars in this study in some cases appeared to respond positively to N rate in excess of 80 kg ha^{-1} (Mohr et al. 2009, 2010).

The apparent contribution from the applied fertilizer to N_2O emissions was evaluated by calculating the EF_{gs}. The overall growing season average value of 0.73% was comparable with the values of 0.2–0.8% observed in a rain-fed study in New Brunswick which covered a comparable monitoring period [calculated from Burton et al. (2008b)] but lower than the IPCC Tier II EF_{irri} value of 1.72% for irrigated cropland in Canada (Rochette et al. 2008). It should, however, be noted that emissions during winter and spring thaw were considered in the Rochette et al. (2008) study but not in the current study. Recent studies under both field and laboratory conditions for other sites within the Black Soil zone in Manitoba suggest that substantial emissions occur during spring thaw (Dunmola et al. 2010; Glenn et al. 2012) and enhanced denitrification in the presence of NO_3^- results in N_2O emissions (Tenuta and Sparling 2011). Over 4 yr at the Trace Gas Manitoba research site near Winnipeg, MB, with near continuous year-long micrometeorological monitoring of annual crops on clay, N_2O emissions over winter and thaw averaged 23% of the annual emissions (Stewart 2010; Glenn et al. 2012). Closer to the current study area and just north east of Brandon, MB, Dunmola et al. (2010) reported on a clay loam soil thaw emissions to be approximately 35 and 26% of total annual emissions for a wheat year and a flax year, respectively. Using the DNDC model, Smith et al. (2010) suggested that winter and spring thaw emissions from agricultural soils in Canada accounted for 30% of the annual total. Using a similar adjustment of 30%, the whole-year emission factor (EF_{wy}) in the current study is 1.04%. Therefore, the EF_{wy} for this study appeared to be less than the proposed IPCC Tier II value of 1.72% for irrigated cropland and closer to the estimate of 0.8% for the Black Soil zone of the Canadian prairies for non-irrigated cropland.

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 a 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-textured soil due to the lower organic C content and water-holding capacity (Bouwman et al. 2002). Rochette et al. (2008) proposed a Canadian IPCC Tier II value of 1.72% for irrigated cropland, assuming that water input (rain plus irrigation) equaled potential evapotranspiration (PET) May through October thus imposing no water limitation to N_2O emissions. We estimated PET from May through October for the 2 study years using Eq. 1 of Baier and Robertson (1965) used by Rochette et al. 2008 (P. Rochette, personal communication). The calculated PET was 575 mm and 602 mm, compared with total water input of 344 mm and 480 mm in 2009 and 2010, respectively. The ratio of water input/PET*100 for our study was therefore 60% and 80% in 2009 and 2010, respectively. Estimates based upon Shaykewich et al. (1998) showed for irrigated Russet Burbank and Shepody potato grown in the same location as in the current study, water input was 64% of PET. The less water input than PET suggests that irrigation in potato field in Manitoba usually is not applied frequent enough to meet PET. In addition, a crop coefficient should be considered when estimating the amount of irrigation (Raddatz et al. 1996). Thus, water may have restricted N_2O emission in the current study despite being irrigated cropland, resulting in EF_{wy} being more similar to that for the Black Soil zone. It should be noted that Rochette et al. (2008) used climate normal while this study refers to 2 specific years. Of course, more studies concerning different crop systems on different soil types are required to improve the national inventories of N_2O emissions.

Not surprisingly, the significantly higher EF_{gs} in 2010 than 2009 suggests that a greater proportion of fertilizer N tends to be lost as N_2O in years with more moisture input. Generally, at N additions more than crop requirement, a greater percentage of the fertilizer N applied will be emitted as N_2O because of a greater amount of N available for soil nitrifying and denitrifying organisms (van Groenigen et al. 2010). In the current study, however, while applying N fertilizer at 240 kg ha^{-1} significantly increased EF_{gs} over that of the 80 kg ha^{-1} N rate in 2009, the overall ANOVA and linear regression analysis (data not shown) showed an insignificant main effect of fertilizer rate (Table 2). The lack of a fertilizer impact could be partly due to the high EF_{gs} for the 80 kg ha^{-1} treatment in 2010. In the current study, N_2O emission episodes following planting and hilling occurred when crop uptake of N would be minimal. At these times the crop was not beyond potato growth stage II and N uptake would not be greater than 0.3 kg N ha^{-1} d^{-1} (Heard 2004). Thus, a large proportion of fertilizer N was available as substrate for soil microorganisms relative to crop uptake, even at the lowest N addition rate of 80 kg ha^{-1}.

Consistent with the results of previous studies with potato and other crops (Smith et al. 1998; Ruser et al. 2001; McSwiney and Robertson 2005; Burton et al. 2008b; Zebarth et al. 2008; Jiang et al. 2011; Glenn et al. 2012), high rates of N_2O emissions shortly after ammonium-based N fertilizer additions were always associated with heavy rainfall ($>$20 mm) or irrigation events in the current study. This suggests denitrification was 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. When the soils were drained and well-aerated, nitrification likely became increasingly important as the rate of nitrification may be stimulated by the enhanced availability of NH_4^+, and N_2O formation may rise due to chemical decomposition of nitrite (NO_2^-) or reduction of NO_2^- via nitrifier denitrification (Wrage et al. 2004). While the current experimental design did not allow us to distinguish the sources of N_2O, Panek et al. (2000) used labelled ^{15}N in an irrigated and fertilized wheat system and found that nitrification at lower soil moistures and denitrification at high moisture periods contributed equally to total N_2O losses over the growing period. In the present study, it is likely that denitrification was more important in wetter 2010, the growing season with higher cumulative N_2O emissions (Table 2), as well as the fact that there were two major emission episodes related to the timing of N application and the onset of water additions in 2010 but only one in 2009 (Fig. 1). These differences between years were largely associated with the greater and more frequent water additions by precipitation and irrigation events in 2010 than 2009. The results suggest that avoiding water-saturated conditions shortly after application of N fertilizer is of importance in limiting N_2O emissions.

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. Furthermore, N_2O emission following fertilizer application at seeding were mainly from the furrow position. Variations in N_2O emissions between hills and furrows were reported in other studies with varying results. Smith et al. (1998) reported N_2O emission from furrows were about three times higher than those from hills in potato fields in Scotland, which was attributed to the higher denitrification rate induced by higher soil moisture content and reduced aeration. Burton et al. (2008b), however, observed higher N_2O emissions at hill relative to the furrow on a loam to sandy loam soil in New Brunswick and suggested this could be due to the higher gaseous diffusion or higher concentrations of NO_3^- in the hill. In the present study, in the relatively dry year of 2009 (total growing season precipitation was 15% less than climate normal), accumulation of broadcast fertilizer toward hill position by the hilling operation could have resulted in higher soil NO_3^- concentrations in the hills compared with the furrows. In contrast to the fertilizer applied at hilling, 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, different hilling implements were used in each of the 2 study years with the implement used in 2010 having caused less movement of soil to 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).

CONCLUSION

By monitoring 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. Emission of N_2O increased following fertilizer application and water addition events, with the different response between furrows and hills. Cumulative N_2O emissions and yield based N_2O intensity increased linearly with N application rate, suggesting 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 was 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 Canadian 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 PET equaled total water input may be responsible for a lower than expected EF_{wy}. Thus, the results suggest it may not be suitable to assume total water input equals 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 textured soil are required for a more robust assessment of nitrogen fertilizer EF across this zone.

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Agriculture and Agri-Food Canada. 2002. Canadian fertilizer consumption, shipments and trade. [Online] Available: http://www.cfi.ca/_documents/uploads/elibrary/cf01_02_e[1].pdf [2012 Apr. 10]
Beauchamp, E. G. 1997. Nitrous oxide emission from agricultural soils. Can. J. Soil Sci. **77**: 113–123.
Baier, W. and Robertson, G. W. 1965. Estimation of latent evaporation from simple weather observations. Can. J. Plant Sci. **45**: 276–284.
Bouwman, A. F., Boumans, L. J. M. and Batjes, N. H. 2002. Emissions of N_2O and NO from fertilised fields: Summary of available measurement data. Glob. Biogeochem. Cycle. **16**: 1058.
Buchkina, N. P., Balashov, E. V., Rizhiya, E. Y. and Smith, K. A. 2010. Nitrous oxide emissions from a light-textured arable soil of North-Western Russia: effects of crops, fertilizers, manures and climate parameters. Nutr. Cycl. Agroecosys. **87**: 429–442.
Burton, D. L., Li, X. and Grant, C. A. 2008a. Influence of fertilizer nitrogen source and management practice on N_2O emissions from two Black Chernozemic soils. Can J. Soil Sci. **88**: 219–227.
Burton, D. L., Zebarth, B. J., Gillam, K. M. and MacLeod, J. A. 2008b. Effect of split application of fertilizer nitrogen on N_2O emissions from potatoes. Can. J. Soil Sci. **88**: 229–239.
Crutzen, P. J. 1981. Atmospheric chemical process of the oxides of nitrogen including nitrous oxide. Pages 17–44 *in* C. C. Delwiche, eds. Denitrification, nitrification and atmospheric nitrous oxide. Wiley, New York, NY.
Desjardins, R. L., Vergé, X., Hutchinson, J., Smith, W., Grant, B., McConkey, B. and Worth, D. 2005. Greenhouse gases. Pages 142–149 *in* A. Lefebvre, W. Eilers, and B. Chunn, eds. Environmental sustainability of Canadian agriculture: Agri-environmental indicator report series – Report #2, Agriculture and Agri-Food Canada, Ottawa, ON.
Dunmola, A. S., Tenuta, M., Moulin, A. P., Yapa, P. and Lobb, D. A. 2010. Pattern of greenhouse gas emission from a Prairie Pothole agricultural landscape in Manitoba, Canada. Can. J. Soil Sci. **90**: 243–256.
Flessa, H., Ruser, R., Schilling, R., Loftfield, N., Munch, J. C., Kaiser, E. A. and Beese, F. 2002. N_2O and CH_4 fluxes in potato fields: automated measurement, management effects and temporal variation. Geoderma **105**: 307–325.
Gillam, K. M., Zebarth, B. J. and Burton, D. L. 2008. Nitrous oxide emissions from denitrification and the partitioning of gaseous losses as affected by nitrate and carbon addition and soil aeration. Can. J. Soil Sci. **88**: 133–143.
Glenn, A. J., Tenuta, M., Amiro, B. D., Stewart S. E. and Wagner-Riddle, C. 2012. Nitrous oxide emissions from an annual crop rotation on poorly drained soil on the Canadian Prairies. Agr. Forest. Meteorol. (in press).
Granli, T. and Bøckman, O. C. 1994. Nitrous oxide from agriculture. Norw. J. Agric. Sci. (Suppl.) **12**: 128 pp.
Haile-Mariam, S., Collins, H. P. and Higgins, S. S. 2008. Greenhouse gas fluxes from an irrigated sweet corn (*Zea mays* L.)-potato (*Solanum tuberosum* L.) rotation. J. Environ. Qual. **37**: 759–771.
Heard, J. 2004. Nutrient accumulation and partitioning by potatoes in Manitoba. *In* Proceedings of the Manitoba Soil Science Society. Manitoba Soil Science Society, Winnipeg, MB.
Hutchinson, G. L. and Livingston, G. P. 1993. Use of chamber systems to measure trace gas fluxes. Pages 63–78 *in* L. A. Harper, et al. eds. Agro-ecosystem effect on radiatively important trace gases and climate change. Spec. Publ. ASA, Madison, WI.
Hyatt, C. R., Venterea, R. T., Rosen, C. J., McNearney, M., Wilson, M. L. and Dolan, M. S. 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.
Intergovernmental Panel on Climate Change. 2006. IPCC guidelines for national greenhouse gas inventories. *In* S. Eggleston et al., eds. Agriculture, forestry and other land use. Vol. 4. IGES, Japan.
Jiang, J., Xiong, Z. and Yan, X. 2011. Fertilizer-induced emission factors and background emissions of N_2O from vegetable fields in China. Atmos. Environ. **45**: 6923–6929.
Kaiser, E. A., Kohrs, K., Kücke, M., Schnug, E., Heinemeyer, O. and Munch, J. C. 1998. Nitrous oxide release from arable soil: importance of N fertilization, crops and temporal variation. Soil Biol. Biochem. **30**: 1553–1563.
Kool, D. M., Wrage, N., Zechmeister-Boltenstern, S., Pfeffer, M., Brus, D., Oenema, O. and Van Groenigen, J. W. 2010. Nitrifier denitrification can be a source of N_2O from soil: a revised approach to the dual-isotope labelling method. Eur. J. Soil Sci. **61**: 759–772.
Loveland, P. J. and Whalley, W. R. 1991. Particle size analysis. Pages 271–328 *in* K. A. Smith and C. E. Mullins, eds. Soil analysis, physical methods. Marcel Dekker, Inc., New York, NY.
Manitoba Agriculture, Food and Rural Initiatives. 2009. Guide to crop protection. [Online] Available: http://www.gov.mb.ca/agriculture/crops/cropproduction/gaa01d01.html [2012 Apr. 10].
Manitoba Soil Fertility Guide. 2004. [Online] Available: http:www.gov.mb.ca/agriculture/soilwater/nutrient/fbd02s00.html [2012 Apr. 10].
Malhi, S. S. and Lemke, R. 2007. Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle. Soil Tillage Res. **96**: 269–283.
McSwiney, C. P. and Robertson, G. H. 2005. Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. Global Change Biol. **11**: 1712–1719.
Mills, G. F. and Haluscha, P. 1995. Soils of the Manitoba Crop Diversification Center. Special Report 95–1, Manitoba Soil Resource, Winnipeg, MB.
Mohr, R., Bizimungu, B. and Tomasiewicz, D. 2009. Canada–Manitoba Crop Diversification Centre (CMCDC) 2009 Annual Report. pp. 24–29. [Online] Available: http://www.gov.mb.ca/agriculture/diversification/cmcdc/reports.html.
Mohr, R., Bizimungu, B. and Tomasiewicz, D. 2010. Canada–Manitoba Crop Diversification Centre (CMCDC) 2010 Annual Report. [Online] Available: http://www.gov.mb.ca/agriculture/diversification/cmcdc/reports.html
Panek, J. A., Matson, P. A., Ortiz-Monasterio, I. and Brooks, P. 2000. Distinguishing nitrification and denitrification sources of N_2O in a Mexican wheat system using ^{15}N. Ecol. Appl. **10**: 506–514.
Pedersen, A. R. 2011. HMR: Flux estimation with static chamber data. R package version 0.3.1. [Online] Available: http://CRAN.R-project.org/package=HMR. [2012 Apr. 10].
Raddatz, R. L., Ash, G. H., Shaykewich, C. F., Roberge, K. A. and Graham, J. L. 1996. First- and second-generation

agrometeorological models for the prairies and simulated water-demand for potatoes. Can. J. Soil Sci. **76**: 297–305.
Ravishankara, A. R., Daniel, J. S. and Portmann, R. W. 2009. Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century. Science **326**: 123–125.
Rochette, P., Worth, D. E., Lemke, R. L., McConkey, B. G., Pennock, D. J., Wagner-Riddle, C. and Desjardins, R. L. 2008. Estimation of N_2O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. Can. J. Soil. Sci. **88**: 641–654.
Ruser, R., Flessa, H., Schilling, R., Beese, F. and Munch, J. C. 2001. Effect of crop-specific field management and N fertilization on N_2O emissions from a fine-loamy soil. Nutr. Cycl. Agroecosys. **59**: 177–191.
Ruser, R., Flessa, H., Schilling, R., Steindl, H. and Beese, F. 1998. Effects of soil compaction and fertilization on N_2O and CH_4 fluxes in potato fields. Soil Sci. Soc. Am. J. **62**: 1587–1598.
Shaykewich, C. F., Ash, G. H. B., Raddatz, R. L. and Tomasiewicz, D. J. 1998. Field evaluation of a water use model for potatoes. Can. J. Soil Sci. **78**: 441–448.
Smith, K. A., McTaggart, I. P., Dobbie, K. E. and Conen, F. 1998. Emissions of N_2O from Scottish agricultural soils, as a function of fertilizer N. Nutr. Cycl. Agroecosys. **52**: 123–130.
Smith, W. N., Grant, B. B., Desjardins, R. L., Worth, D., Li, C., Boles, S. H. and Huffman, E. C. 2010. A tool to link agricultural activity data with the DNDC model to estimate GHG emission factors in Canada. Agric. Ecosyst. Environ. **136**: 301–309.
Statistics Canada. 2011. Service bulletin. Canadian potato production. [Online] Available: http://www.statcan.gc.ca/pub/22-008-x/22-008-x2011002-eng.pdf. [2012 Apr. 10].
Stewart, S. E. 2010. Perennial legume phase and annual crop rotation influences on CO_2 and N_2O fluxes over two years in the red river valley, Manitoba, Canada. MSc thesis. University of Manitoba, Winnipeg, MB.
Tenuta, M., Mkhabela, M., Tremorin, D., Coppi, L., Phipps, G., Flaten, D. and Ominski, K. 2010. Nitrous oxide and methane emission from a coarse-textured grassland soil receiving hog slurry. Agri. Ecosyst. Environ. **138**: 35–43.
Tenuta, M. and Sparling, B. 2011. A laboratory study of soil conditions affecting emissions of nitrous oxide from packed cores subjected to freezing and thawing. Can. J. Soil Sci. **91**: 223–233.
Tiessen, H. and Moir, J. O. 1993. Total organic carbon. Pages 187–200 *in* M. R. Carter, ed. Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.
Vallejo, A., Skiba, U. M., Garcia-Torres, L., Arce, A., Lopez-Fernandez, S. and Sanchez-Martin, L. 2006. Nitrogen oxide emissions from soils bearing a potato crop as influenced by fertilization with treated pig slurries and composts. Soil Biol. Biochem. **38**: 2782–2793.
van Groenigen, J. W., Velthof, G. L., Oenema, O., van Groenigen, K. J. and van Kessel, C. 2010. Towards an agronomic assessment of N2O emissions: a case study for arable crops. Eur. J. Soil Sci. **61**: 903–913.
Venterea, R. T., Hyatt, C. R. and Rosen, C. J. 2011. Fertilizer management effects on nitrate leaching and indirect nitrous oxide emissions in irrigated potato production. J. Environ. Qual. **40**: 1103–1112.
Western Potato Council. 2003. Guide to commercial potato production on the Canadian prairies. [Online] Available: http://www1.agric.gov.ab.ca/%24department/deptdocs.nsf/all/opp9546.
Wrage, N., Velthof, G. L., Laanboek, H. J. and Oenema, O. 2004. Nitrous oxide production in grassland soils: assessing the contribution of nitrifier denitrification. Soil Biol. Biochem. **36**: 229–236.
Zebarth, B. J., Leclerc, Y., Moreau, G., Gareau, R. and Milburn, P. H. 2003. Soil inorganic nitrogen content in commercial potato fields in New Brunswick. Can. J. Soil Sci. **83**: 425–429.
Zebarth, B. J., Rochette, P., Burton, D. L. and Price, M. 2008. Effect of fertilizer nitrogen management on N_2O emissions in commercial corn fields. Can. J. Soil Sci. **88**: 189–195.