Controlled release fertilizer product effects on potato crop response and nitrous oxide emissions under rain-fed production on a medium-textured soil

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[1]Potato Research Centre, Agriculture Agri-Food Canada, Fredericton, New Brunswick, Canada E3B 4Z7 (e-mail: bernie.zebarth@agr.gc.ca); [2]Department of Environmental Sciences, Nova Scotia Agricultural College, Truro, Nova Scotia, Canada B2N 5E3; and [3]Agrium Inc., 13131 Lake Fraser Dr SE, Calgary, Alberta, Canada T2J 7E8. *Received 26 January 2012, accepted 5 June 2012.*

Zebarth, B. J., Snowdon, E., Burton, D. L., Goyer, C. and Dowbenko, R. 2012. **Controlled release fertilizer product effects on potato crop response and nitrous oxide emissions under rain-fed production on a medium-textured soil**. Can. J. Soil Sci. **92**: 759–769. Controlled release fertilizers and split fertilizer N applications are expected to provide plant-available nitrogen (N) in synchrony with crop requirements, which should mitigate nitrous oxide (N_2O) emissions from agricultural soils. This study compared a polymer coated urea (PCU) controlled release N fertilizer (Environmentally Smart Nitrogen), split fertilizer N application and conventional fertilizer N management on the crop response and growing season N_2O emissions from rain-fed potato (*Solanum tuberosum* L.) production on a medium-textured soil in Atlantic Canada from 2008 to 2010. Fertilizer were applied at the recommended rate (193 kg N ha^{-1}) and treatments included the PCU product banded at planting, conventional fertilizer in a split application (60% as diammonium phosphate plus ammonium nitrate at planting plus 40% as ammonium nitrate at final hilling), conventional fertilizer (diammonium phosphate plus ammonium nitrate) banded at planting, and an unfertilized control. Within each year, cumulative growing season N_2O emissions were closely related to soil nitrate availability as measured by nitrate exposure (sum of daily nitrate concentration in the surface soil). Split N application had no effect on crop response, and significantly reduced nitrate exposure, but did not reduce N_2O emissions. With the PCU, there was evidence of increased plant N availability and greater N_2O emissions. In situations where the risk of nitrate leaching is limited, substitution of a PCU product for conventional fertilizer at the same N application rate will not necessarily reduce growing season N_2O emissions and may in some cases increase the risk of N_2O emissions. Further research is required to determine if lowering N rates with PCU products will be effective agronomically and environmentally.

Key words: Environmentally Smart Nitrogen, polymer coated urea, nitrate exposure, soil nitrate, Nitrogen Nutrition Index, petiole nitrate concentration, *Solanum tuberosum*

Zebarth, B. J., Snowdon, E., Burton, D. L., Goyer, C. et Dowbenko, R. 2012. **Incidence des engrais à libération lente sur le rendement de la pomme de terre et sur les émissions d'oxyde nitreux dans les sols non irrigués de granulométrie moyenne**. Can. J. Soil Sci. **92**: 759–769. L'application d'engrais à libération lente ou leur application fractionnée devrait procurer aux plantes suffisamment d'azote (N) assimilable, en synchronisme avec les besoins de la culture, ce qui devrait réduire les émissions d'oxyde nitreux (N_2O) des sols agricoles. La présente étude compare l'incidence des engrais N à libération lente à base d'urée enrobée de polymère (PCU), aussi appelés azote écologique, de l'application fractionnée d'engrais N et des pratiques courantes d'amendement sur la réaction de la culture et sur les émissions saisonnières de N_2O pour la pomme de terre (*Solanum tuberosum* L.) cultivée sans irrigation sur un sol de texture moyenne, dans les provinces de l'Atlantique, de 2008 à 2010. L'engrais a été appliqué au taux recommandé (193 kg de N par hectare) et les traitements consistaient en l'application de PCU en bandes à la plantation, l'application fractionnée d'engrais ordinaire (60 % de phosphate diammonique et de nitrate d'ammonium à la plantation plus 40 % de nitrate d'ammonium au buttage), l'application d'engrais classique (phosphate diammonique et nitrate d'ammonium nitrate) en bande à la plantation et aucune application d'engrais (témoin). Chaque année, les émissions saisonnières cumulatives de N_2O étaient étroitement reliées à la quantité de nitrates disponible dans le sol, établie d'après l'exposition aux nitrates (somme de la concentration quotidienne de nitrates dans le sol de surface). L'application fractionnée de N n'a eu aucune incidence sur la réaction des cultures et a atténué sensiblement l'exposition aux nitrates sans toutefois réduire les émissions de N_2O. L'application de PCU entraîne une hausse de la concentration de N disponible pour les plantes et une hausse des dégagements de N_2O. Quand il y peu de risques de lixiviation des nitrates, remplacer l'engrais PCU par un engrais ordinaire au même taux

Abbreviations: **CRF**, controlled release fertilizer; **ESN**, Environmentally Smart Nitrogen; **NE**, nitrate exposure; **NNI**, nitrogen nutrition index; **PCU**, polymer coated urea

d'application ne diminuera pas nécessairement les émissions saisonnières de N_2O et pourrait même parfois les augmenter. Il faudrait entreprendre d'autres recherches pour établir si un taux d'application plus faible des engrais PCU s'avérerait efficace sur le plan de l'agronomie et sur celui de l'environnement.

Mots clés: Azote écologique, urée enrobée de polymère, exposition aux nitrates, nitrates du sol, indice nutritif de l'azote, concentration de nitrates dans le pétiole, *Solanum tuberosum*

Agricultural soils are the primary source of anthropogenic nitrous oxide (N_2O) emissions (Environment Canada 2010) and the N_2O emissions are associated primarily with the processes of denitrification and nitrification (Mosier 1998). Under the humid soil moisture regimes of Atlantic Canada, N_2O emissions in field and laboratory experiments were associated primarily with the denitrification process (Burton et al. 2008; Gillam et al. 2008). The risk of N_2O emissions is increased when soil nitrate (NO_3^-) concentrations are increased (Gillam et al. 2008). Consequently, there is concern about the magnitude of N_2O emissions from potato production due to the relatively high fertilizer N inputs (Zebarth et al. 2003a), the presence of high soil NO_3^- concentrations during the growing season particularly in the ridge (Zebarth and Milburn 2003), and the potential for large quantities of residual NO_3^- in the root zone after tuber harvest (Cambouris et al. 2008).

Improved fertilizer N management practices, including split fertilizer N applications, use of controlled release fertilizer (CRF) products and nitrification inhibitors, have been identified as options for mitigation of N_2O emissions (Smith et al. 1997; Akiyama et al. 2010). The potato crop is sensitive to NH_4-N and the use of nitrification inhibitors can result in loss of tuber yields in some cases (Slangen and Kirkhoff 1984; Prasad and Power 1995), and consequently use of nitrification inhibitors will not be considered further in this study.

Split fertilizer N application has been shown to be effective in improving the efficiency of N utilization in potato production systems, particularly in situations where the risk of NO_3^- leaching is high (Errebhi et al. 1998). The benefit of split application has been attributed primarily to a reduction in NO_3^- leaching potential (Harris 1992). In Atlantic Canada, where rain-fed potato production is primarily on medium-textured soils, most NO_3^- leaching occurs outside of the crop growing season (Milburn et al. 1990, 1997). In this region, split N application did not provide a consistent benefit with respect to potato yield or N use efficiency under normal rainfall conditions (Porter and Sisson 1993; Zebarth et al. 2004a, b). In some years under dry soil conditions, which may limit crop N uptake, split N application resulted in reduced tuber yield and N use efficiency (Porter and Sisson 1993; Zebarth et al. 2004a, b). Split fertilizer N application was compared with application of all fertilizer N at planting in 2 yr under rain-fed potato production in Atlantic Canada (Burton et al. 2008). Split N application reduced N_2O emissions in 1 yr when most N_2O emissions occurred between planting and split N application, but had no significant effect in the second year.

Application of CRF products increased the efficiency of N utilization in potato production in several studies (Shoji et al. 2001; Zvomuya et al. 2003; Ziadi et al. 2011). Like split N application, the use of CRF products is most effective in situations where the risk of NO_3^- leaching is high (Liegel and Walsh 1976). Compared with split N application, use of CRF in irrigated potato production on sandy soils reduced NO_3^- leaching during the growing season and increased apparent fertilizer N recovery in the potato crop (Zvomuya et al. 2003; Wilson et al. 2010) and resulted in comparable tuber yield, size and net returns from treatments having comparable N supply (Wilson et al. 2009). The use of polymer coated urea (PCU) in irrigated potato production on sandy soils also reduced N_2O emissions compared with split N applications (Hyatt et al. 2010). However, for the rain-fed potato production in medium-textured soils of Atlantic Canada, it is unclear if there will be a beneficial effect of PCU products on N utilization or on N_2O emissions.

In Atlantic Canada where the risk of NO_3^- leaching during the growing season is limited, split N applications and CRF products are expected to be effective in reducing growing season N_2O emissions primarily because they reduce soil NO_3^- concentrations, at least temporarily, and hence the availability of NO_3^- for the denitrification process. The availability of NO_3^- for the denitrification process can be estimated as nitrate exposure (NE), previously referred to as "nitrate intensity" by Burton et al. (2008). The NE is a time-integrated measure of soil NO_3^- concentration, and is calculated as the sum of the daily soil NO_3-N concentration in the surface soil horizon. The NE was positively correlated with cumulative growing season N_2O emissions in potato and barley crops (Burton et al. 2008; Zebarth et al. 2008).

The objective of this research was to examine the effect of using a PCU product on crop response and on growing season N_2O emissions from rain-fed potato production in Atlantic Canada. The PCU product was compared with conventional fertilizer N management, which is band application of all fertilizer N at planting, and with split N application. The PCU product chosen was Environmentally Smart Nitrogen (ESN) (Agrium Inc., Calgary, AB), which has an analysis of 44–0–0. The ESN product has a lower cost compared with previous CRF products and is economically viable for use in potato production (Wilson et al. 2009). This study also examined if NE could be used as an indicator of the relative risk of N_2O emissions associated with different fertilizer N management practices. On medium-textured soils in eastern Canada, where NO_3^- leaching is limited during the growing season (Milburn et al. 1990), we hypothesized that use of a PCU product and split N application would reduce the duration of high soil NO_3^- concentrations and thereby reduce the risk of growing season N_2O emissions.

MATERIALS AND METHODS

Field trials were conducted from 2008 to 2010 at the Potato Research Centre of Agriculture and Agri-Food Canada, Fredericton, NB, Canada (lat. 45°55′N; long. 66°36′W). The preceding crop for each trial was barley (*Hordeum vulgare* L.), the most common potato rotational crop in New Brunswick. Soils at the experimental site belong to the Research Station soil association (coarse loamy morainal ablational till over coarse loamy morainal lodgement till), and are classified as Orthic Humo-Ferric Podzols (Rees and Fahmy 1984). Soil properties for the 0- to 15-cm depth were soil pH (1:1 water) of 6.2, and soil organic C and total N concentrations (LECO CNS–1000) of 19.2 g C kg^{-1} and 1.67 g N kg^{-1}, respectively. Soil textural class (pipette method with organic matter removal) was loam with 490 g kg^{-1} sand, 390 g kg^{-1} silt and 110 g kg^{-1} clay.

The trials used a randomized complete block design with four N fertility treatments and four replications. The N fertility treatments included: (1) a control, which received no fertilizer N; (2) conventional fertilizer N management for Atlantic Canada, which consists of all N banded at planting as diammonium phosphate plus ammonium nitrate; (3) split N application with 60% of N banded at planting as diammonium phosphate plus ammonium nitrate and 40% of N broadcast and incorporated at final hilling as ammonium nitrate; and (4) all N banded at planting as ESN. The fertilizer N application rate was 193 kg N ha^{-1} for all three N sources, the recommended rate for this field site with barley as a preceding crop (Zebarth et al. 2007). Additional fertilizer was applied such that all treatments received the same application rate of P and K. Plots were six rows (5.5 m) by 20 m in size, with the two outer rows acting as guard rows.

Potatoes were hand-planted using hand-cut potato seed, cultivar Russet Burbank, on 2008 May 22, 2009 May 22 and 2010 May 13 using a 0.91-m row spacing and 0.41-m within-row spacing. Fertilizer N was banded at planting approximately 7.5 cm to each side and 5 cm below the seed pieces. Split N application was applied on 2008 Jul. 04, 2009 Jul. 10 and 2010 Jul. 05 in conjunction with final hilling (i.e., ridge formation). Standard commercial practices were used for disease, insect and weed control. No irrigation was applied.

Whole plant samples were collected on 2008 Aug. 26, 2009 Sep. 10 and 2010 Aug. 30 prior to vine desiccation. Four adjacent plants in each of two rows were sampled, the plants partitioned into three components (vines, tubers, and below-ground stem plus stolons plus readily-recoverable roots) and the dry matter and N accumulation of each component was determined as described previously by Zebarth and Milburn (2003). Plant N accumulation at this time was used as a measure of N availability within the different treatments. In addition, the nitrogen nutrition index (NNI) was calculated as described by Bélanger et al. (2001) as the ratio of the measured N concentration in the plant biomass (vines plus tubers) to the critical N concentration (N_c). The N_c for cultivar Russet Burbank was predicted using the following equation:

$$N_c = 4.57\ W^{-0.42} \tag{1}$$

where W is plant (i.e., vines plus tubers) biomass (t ha^{-1}) and N_c has units of % N.

Vine desiccation was done on 2008 Sep. 26, 2009 Sep. 14 and 2010 Sep. 15 using the herbicide diquat, and total tuber yield was determined on 2008 Oct. 08, 2009 Oct. 13–14 and 2010 Oct. 04–05 using two rows from each plot. Tuber size was estimated as the average weight of tubers greater than 5 cm diameter. Tuber specific gravity was determined using the weight-in-water and weight-in-air method using an approximately 4.5-kg sample of medium-sized tubers.

Petioles were sampled approximately biweekly beginning 45–55 d after planting for determination of petiole nitrate concentration. In each case, one petiole from the last fully expanded leaf, commonly the fourth leaf from the top of the plant, was collected from 20 randomly selected plants in each plot and oven dried at 60°C. Petiole samples were ground to pass a 2-mm screen. Using a method similar to that of Porter and Sisson (1991), a 0.2-g subsample was extracted with distilled-deionized water using a 1:20 sample:extractant ratio and 15 min shaking time. The extract was diluted 25:1 using an automated diluter, and NO_3-N concentration in the extract determined as described by Zebarth et al. (2003b).

N_2O and CO_2 flux measurements were made using a non-flow-through, non-steady-state chamber with a total volume of 1.6 L, covering a soil area of 315 cm^2 (Burton et al. 2008). All plants and plant material were removed from the inner collar area. Gas samples were collected over a 30-min deployment period, with samples collected at 0, 10, 20 and 30 min (Burton et al. 2008). Gas samples were collected by removing 20 mL of gas from the headspace of the chamber and injecting it into a pre-evacuated (to 500 millitorr) 12-mL Exetainer (Labco, UK). Replicate exetainers containing breathing grade oxygen ($n = 5$) and 8.8 $\mu L\ L^{-1}$ N_2O ($n = 5$) were prepared as quality controls on each sampling date (Burton et al. 2008).

N_2O and CO_2 measurements were taken approximately weekly from 2008 May 20 to Oct. 21, 2009 May 13 to Oct. 09 and 2010 May 10 to Sep. 20. Two collars were installed in each plot in early spring and remained in place until planting. After planting, two collars were reinstalled in each of the ridge and furrow row locations of each plot. All collars were removed prior to hilling and re-installed immediately upon completion of hilling, and remained in place until final tuber harvest. After final harvest, two collars were re-installed in each plot.

As described by Burton et al. (2008), N_2O and CO_2 (g N_2O-N ha^{-1} d^{-1} and kg CO_2-C ha^{-1} d^{-1}) fluxes were calculated using the following equation (Hutchinson and Livingston 1993):

$$N_2O = dC/dt \; Vc\mathrm{Mmol}/A\mathrm{Vmol} \tag{2}$$

where dC/dt is the rate of change in N_2O concentration, A is the surface area (m^2) of the chamber, Vc is the total volume (L) of the chamber, Mmol is the molar mass of N_2O (g mol^{-1}) and Vmol is the volume of a mole of N_2O (L mol^{-1}) inside the chamber corrected for temperature using the ideal gas law. The flux value of dC/dt was calculated using the simple linear regression of the gas concentrations versus time over the deployment period. All flux values were adjusted to represent grams of N and kg of C per hectare per day. Cumulative growing season gas fluxes were calculated from the date of planting to the date of tuber harvest (139, 143 and 141 d period for 2008, 2009 and 2010, respectively) by linear interpolation between sampling dates, following the assumption that gas flux measured on the sampling date was representative of the average daily flux. The ridge and furrow positions were assumed to represent approximately similar areas within the field, and consequently the average flux of the two row locations was assumed to represent average emissions from the field.

Soil samples for determination of soil mineral N concentrations were collected from each plot on each date that N_2O and CO_2 fluxes were measured. Samples consisted of a composite of eight soil cores, 2.54 cm in diameter. Pre-plant and post-harvest soil samples were collected from 0- to 10-cm depth randomly within the plot. Post-planting, soil samples were collected from 0- to 10-cm depth separately from the ridge and furrow locations. After hilling, the depth for soil samples collected from the ridge location was adjusted to 0- to 20-cm to reflect the greater depth of the soil A horizon. The soils were stored at 4°C and processed within 24 h. All soil samples were passed through a 4.75-mm sieve, and a 20 g sub-sample was dried at 105°C for 48 h to determine gravimetric water content. A 25 g sub-sample of moist soil was extracted with 0.5 M K_2SO_4 using a 1:2 soil:extractant ratio and a shaking time of 30 min (Miller et al. 2008). Extracts were filtered and stored at −20°C pending analysis. Concentrations of NO_3^--N and NH_4^+-N were determined colorimetrically using a Technicon Auto Analyzer II system following Technicon Industrial Method #100-70W and Technicon Industrial Method #98-70W, respectively. Blank samples were also run to account for background levels in the procedure.

Nitrate exposure (previously defined as nitrate intensity) was calculated as the linear interpolation of the NO_3^--N concentrations between sampling dates for the same time period as cumulative growing season N_2O emissions (Burton et al. 2008). It is expressed in units of g N d kg^{-1}, which combines both the magnitude of NO_3^--N concentrations and the duration when they are present. This measure gives a temporally integrated measure of the exposure of the soil microbial community to the NO_3 over the growing season.

Analysis of variance (ANOVA) was performed using the General Linear Model of SAS. Statistical comparisons among treatment mean values were performed using a protected LSD test. Relationships among measured parameters were assessed by regression analyses using the General Linear Model of SAS. Apparent fertilizer N recovery was calculated using treatment means as plant N accumulation in the fertilized treatment, minus plant N accumulation in the control, divided by the rate of fertilizer N applied and expressed as a percentage.

RESULTS

Growing season (May to September) air temperatures were similar to or slightly warmer than the long-term (1971–2000) average (Table 1). Growing season precipitation in 2008 (404 mm) was 13% below the long-term average of 462 mm. Growing season precipitation was 20% above the long-term average in 2009 and 2010, but the distribution of precipitation differed between years. In 2009, precipitation was above-average in each month

Table 1. Monthly mean air temperature and total precipitation during the growing season for the experimental period in comparison with the 30-yr (1971–2000) climate normals (data from the Fredericton CDA climate station; Environment Canada 2011)

	Air temperature				Precipitation			
Month	2008	2009	2010	30 yr	2008	2009	2010	30 yr
	(°C)				(mm)			
May	10.7	12.0	12.6	11.2	46	83	43	100
Jun.	16.9	16.0	16.1	16.4	91	131	206	92
Jul.	20.8	18.0	20.8	19.3	81	107	80	90
Aug.	18.1	20.0	19.1	18.6	68	133	32	85
Sep.	14.2	13.0	15.3	13.7	118	100	195	95
May–Sep.	16.1	15.8	16.8	15.8	404	554	555	462

from June to September. In 2010, rainfall was more than double the normal value in June and September, and less than half of normal in May and August.

Total tuber yield was greater in 2009 than in 2008 and 2010, whereas mean tuber weight did not differ among years (Table 2). Tuber yield and mean tuber weight were increased by N fertilization, but did not differ among the three treatments which received fertilizer application (i.e., conventional, split N and PCU managements). Tuber specific gravity was greater in 2009 than in 2008 and 2010, and was greater in the control and split N application treatments than for the PCU treatment.

Plant N accumulation measured prior to vine desiccation was greater in 2008 than in 2010 (Table 3). Plant N accumulation was greater for fertilized treatments than for the non-fertilized control. When averaged across years, there was no significant difference in plant N accumulation among fertilized treatments. In 2009, plant N accumulation was numerically greater (30%) for the PCU treatment than for the conventional treatment but this difference was not statistically significant. Apparent fertilizer N recovery in the plant averaged 51, 49 and 58% for the conventional, split N and CRF treatments, respectively.

The NNI calculated prior to vine desiccation was greater, indicating greater N status, in 2008 than in 2009 and 2010 (Table 3). The NNI was greater for fertilized treatments than for the unfertilized control, and greater for the PCU treatment than for the split N treatment. The NNI for the control treatment was less than 1, suggesting the crop was N limited. For the fertilized treatments, the NNI was well above 1, suggesting the N supply in these treatments was greater than what was required by the crop.

Petiole NO_3^- concentrations for the unfertilized control were lower than for fertilized treatments in all 3 yr and would generally be characterized as deficient based on petiole NO_3^- guidelines (Fig. 1). There were no significant differences in petiole NO_3^- concentrations among fertilized treatments in 2008 and 2010. Petiole NO_3^- concentrations for the fertilized treatments were generally in the optimal range in 2008 and above the optimal range in 2010. In contrast, petiole NO_3^- concentrations in 2009 varied among the fertilized treatments: petiole NO_3^- concentrations were greatest for the PCU treatment on all sampling dates and were above the optimal range; petiole NO_3^- concentrations for the split N application were relatively constant over the sampling period; and petiole NO_3^- concentration for the conventional management was greater than for split N application early in the growing season, but lower than for split N application late in the growing season.

N_2O emissions were relatively uniform throughout 2008 regardless of N fertility treatment or row location (Fig. 2a). Rates of N_2O emissions for the ridge location of the conventional and PCU treatments were higher than other N treatments in the ridge position, or any N treatment in the furrow position, on some sampling dates in June and July of 2008. In 2009, N_2O emissions in the ridge location for the control and split N treatments, and in the furrow for all N fertility treatments, were generally low and uniform over time (Fig. 2b). In comparison, N_2O emissions from the ridge location for the PCU treatment were elevated from late June to mid-August, and N_2O emissions from the ridge location of the

Table 2. Total tuber yield, mean tuber weight (>5 cm diameter) and tuber specific gravity as influenced by four N fertility treatments in 3 yr

Treatment	2008	2009	2010	Mean
Total tuber yield (t ha^{-1})				
Control	23.9	20.5	19.1	21.2*a*
Conventional	36.1	41.5	31.3	36.3*b*
Split	32.6	39.3	32.2	34.7*b*
PCU	35.0	41.7	32.0	36.2*b*
Mean	31.9*a*	35.8*b*	28.7*a*	
SEM (27 df; $n = 4$) = 2.6				
Significance: Year *; N treatment *; Year × N treatment NS				
Mean tuber weight (g)				
Control	145	141	153	146*a*
Conventional	182	179	178	180*b*
Split	185	177	170	177*b*
PCU	180	184	191	185*b*
Mean	173	170	173	
SEM (27 df; $n = 4$) = 6.4				
Significance: Year *; N treatment *; Year × N treatment NS				
Specific gravity				
Control	1.090	1.097	1.089	1.092*b*
Conventional	1.084	1.098	1.084	1.089*ab*
Split	1.088	1.103	1.086	1.092*b*
PCU	1.087	1.090	1.083	1.087*a*
Mean	1.087*a*	1.097*b*	1.086*a*	
SEM (27 df; $n = 4$) = 0.002				
Significance: Year *; N treatment *; Year × N treatment NS				

a, *b* Means in the same column or row followed by the same letter are not significantly different based on a protected LSD test.

Table 3. Plant N accumulation and Nitrogen Nutrition Index at vine desiccation for four N fertility treatments in 3 yr

Treatment	2008	2009	2010	Mean
Plant N accumulation (kg N ha^{-1})				
Control	89	65	76	77*a*
Conventional	209	158	159	175*b*
Split	201	159	154	171*b*
PCU	183	206	179	190*b*
Mean	171*b*	147*ab*	142*a*	
SEM (27 df; $n = 4$) = 16.8				
Significance: Year *; N treatment *; Year × N treatment NS				
Nitrogen nutrition index				
Control	0.84	0.64	0.76	0.75*a*
Conventional	1.68	1.25	1.32	1.42*bc*
Split	1.60	1.28	1.29	1.39*b*
PCU	1.55	1.66	1.53	1.58*c*
Mean	1.42*b*	1.21*a*	1.23*a*	
SEM (27 df; $n = 4$) = 0.12				
Significance: Year *; N treatment *; Year × N treatment NS				

a–c Means in the same column or row followed by the same letter are not significantly different based on a protected LSD test.

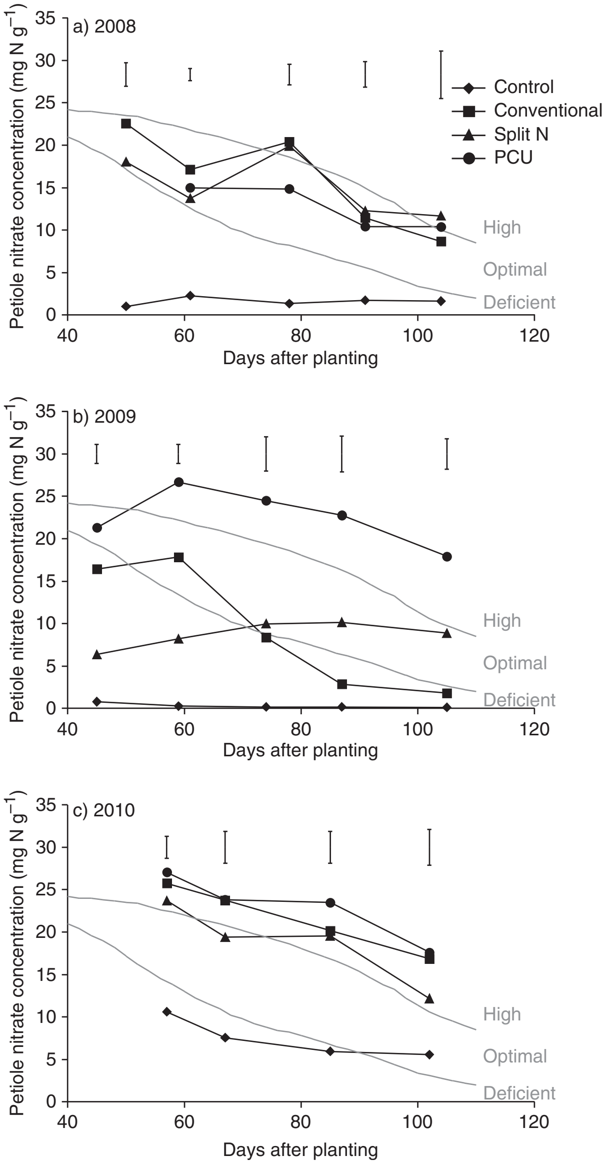

Fig. 1. Petiole NO_3^- concentration for four N fertility treatments in three years. Errors bars indicate ±1 SE. Guidelines for petiole NO_3^- concentrations, indicated in gray, are adapted from Porter and Sisson (1991).

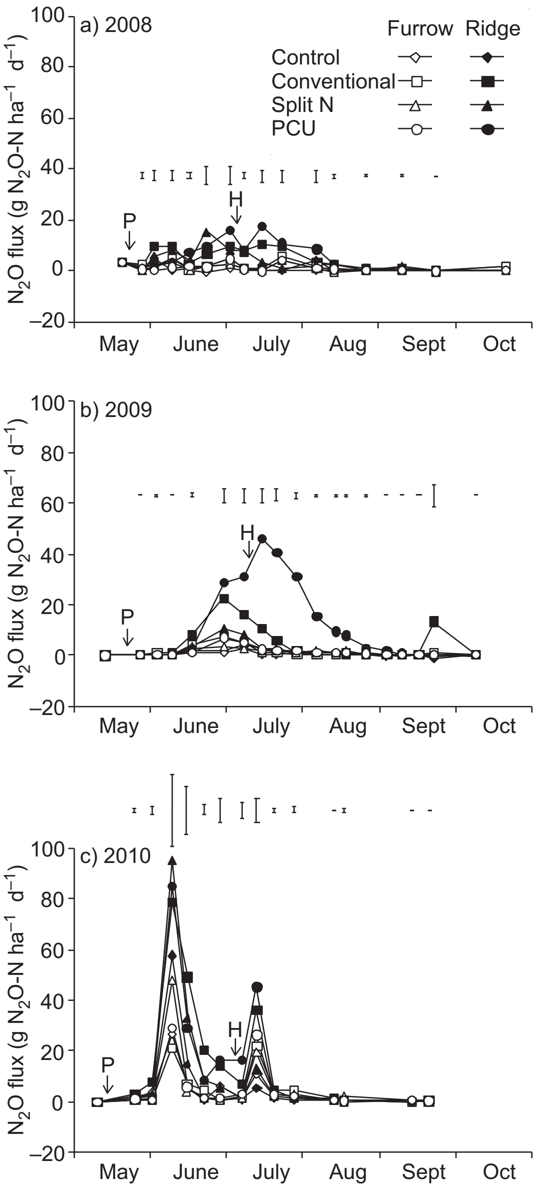

Fig. 2. Soil N_2O flux for four N fertility treatments, measured separately from the potato ridge and furrow locations, over the growing season in 3 yr. Errors bars indicate ±1 SE. The time of planting (P) and final hilling (H) when fertilizer was applied are indicated by arrows.

conventional treatment were elevated from late June to mid-July. In contrast in 2010, elevated N_2O emissions were measured in early June and mid-July regardless of N fertility treatment and row location (Fig. 2c). However, there were limited statistical differences in N_2O emissions among N treatments and row locations over this time period due to high variability.

Cumulative growing season N_2O emissions were greater in 2010 than in 2008 and 2009 (Table 4). Cumulative N_2O emissions, averaged across N fertility treatments, were lower in the furrow (0.28 kg N ha^{-1}) than in the ridge (0.80 kg N ha^{-1}) (data not presented). There was no significant effect of N fertility treatment on N_2O emissions in the furrow, and therefore any treatment differences in emissions are due to variation in emissions from the ridge. When averaged across location and years, N_2O emissions were greater for the fertilized treatments than for the unfertilized control, and greater for the PCU treatment than for the split N treatment (Table 4). N_2O emissions were numerically higher for the PCU treatment than for the other

Table 4. Cumulative growing season N_2O emissions and Nitrate Exposure, averaged across row locations, for four N fertility treatments in 3 yr

Treatment	2008	2009	2010	Mean
Cumulative N_2O emissions (kg N ha^{-1})				
Control	0.12	0.09	0.53	0.25*a*
Conventional	0.42	0.49	1.02	0.64*bc*
Split	0.31	0.22	0.90	0.48*b*
PCU	0.44	0.94	1.00	0.79*c*
Mean	0.32*a*	0.43*a*	0.86*b*	
SEM (27 df; $n = 4$) = 0.12				
Significance: Year *; N treatment *; Year × N treatment NS				
Nitrate exposure (g N d kg^{-1})				
Control	0.90	0.46	0.79	0.72*a*
Conventional	3.25	1.53	2.71	2.50*c*
Split	2.33	1.20	2.50	2.01*b*
PCU	2.67	2.03	2.78	2.49*c*
Mean	2.29*b*	1.31*a*	2.20*b*	
SEM (27 df; $n = 4$) = 0.28				
Significance: Year *; N treatment *; Year × N treatment NS				

a–c Means in the same column or row followed by the same letter are not significantly different based on a protected LSD test.

fertilized treatments in 2009; however, this difference was not statistically significant.

In 2008, soil NO_3^- concentrations for the ridge location of all three fertilized treatments were elevated from early June to mid-August relative to the control treatment and relative to all treatments in the furrow location (Fig. 3a). The primary exception to this was high soil NO_3^- concentrations in the ridge and furrow for the conventional treatment only on the May 28 sampling date. In 2009, soil NO_3^- concentrations in the ridge location for the three fertilized treatments were also generally elevated for most of the growing season; however, the NO_3^- concentrations were lower than in 2008, and in many cases there were no significant differences in soil NO_3^- concentration among treatments within an individual sampling date. In 2010, significantly greater soil NO_3^- concentrations were measured in the ridge for the conventional and PCU treatments in mid to late June (Fig. 3c). On other sampling dates in 2010, soil NO_3^- concentrations in the ridge were sometimes elevated for one of the fertilized treatments, but the pattern was inconsistent over time.

The NE, averaged across N fertility treatment and row location, was lower in 2009 than in 2008 or 2010 (Table 4). The NE was lower in the furrow (1.20 g N d kg^{-1}) than in the ridge (2.66 g N d kg^{-1}) when averaged across years and N fertility treatments (data not presented). Similar to N_2O emissions, NE in the furrow was not influenced by N fertility treatment, and consequently differences in NE among N fertility treatments reflect differences in NE in the ridge location. When averaged across years and locations, NE was greater for the fertilized treatments than for the control, and greater for the PCU and conventional treatments than for the split N treatment. NE was numerically higher for the PCU treatment than for the other fertilized treatments in 2009; however, this difference was not statistically significant.

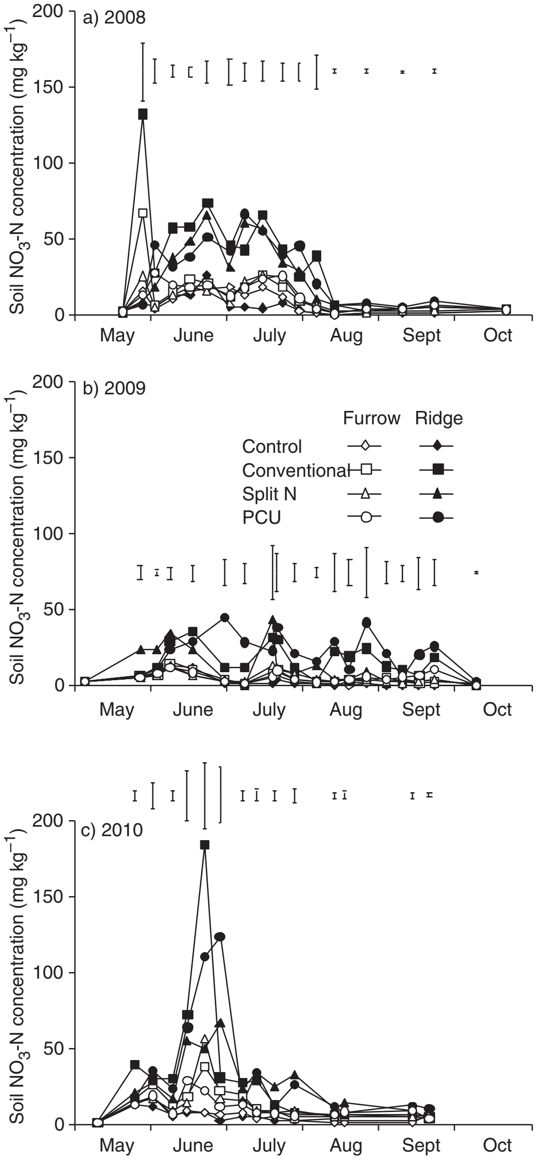

Fig. 3. Soil NO_3-N concentrations for four N fertility treatments measured separately for the surface soil horizon in the potato ridge and furrow locations (0–10 cm depth except for 0–20 cm depth in potato ridge after hilling), over the growing season in 3 yr. Errors bars indicate ±1 SE.

The relationships between cumulative growing season N_2O emissions and NE were examined in each year, where each combination of N fertility treatment and row location was treated separately (Fig. 4). In each year, N_2O emissions increased linearly with NE ($0.87 \le r^2 \le 0.91$) regardless of N fertility treatment and row location. The slope of the regression line varied among years, however, with values of 0.16, 0.51 and 0.33 in 2008, 2009 and 2010, respectively.

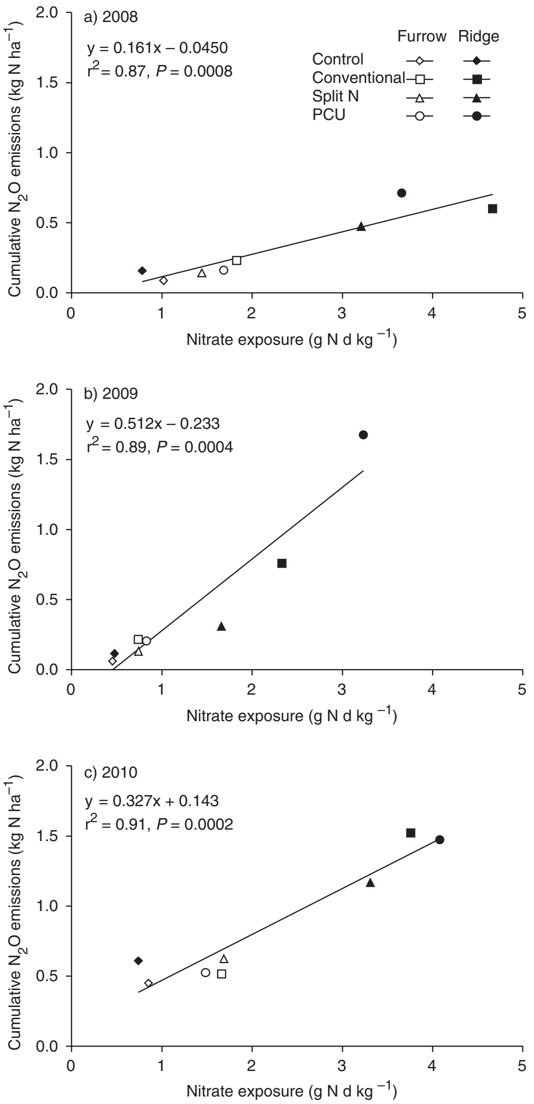

Fig. 4. Relationships between cumulative growing season N_2O emissions and nitrate exposure over four N fertility treatments and two row locations in each of 3 yr.

DISCUSSION

Crop Response and Plant N Status

Tuber yield and mean tuber weight were increased in response to N fertilization, and in some cases tuber specific gravity was reduced by N fertilization. Measures of plant N status, including petiole NO_3^- concentration, NNI and plant N accumulation, were also increased by N fertilization. These responses of the potato crop to N fertilization are consistent with previous studies on potato N fertility (Zebarth and Rosen 2007).

There were few differences in crop responses to N fertilization (i.e., conventional, split N and PCU treatments). There were no differences among these treatments with respect to total tuber yield or mean tuber weight, and only minor differences in tuber specific gravity. Plant N uptake was numerically greater for the PCU treatment than for the conventional and split N application treatments, especially in 2009; however, these differences were not statistically significant. Petiole NO_3^- concentrations were greater for the PCU treatment than the other two fertilized treatments, but only in 2009. The NNI was significantly greater for the PCU treatment than for the split N treatment, and numerically greater than the conventional treatment, primarily reflecting the response of NNI to N treatments in 2009.

The limited differences among treatments receiving fertilizer N may be due in part to the high level of N fertility. Even though the recommended rate of fertilizer was applied, petiole NO_3^- concentrations were in some cases above the optimal range, particularly for the PCU treatment in 2009 and all fertilized treatments in 2010. Similarly, the NNI values for fertilized treatments in this study (1.25–1.66) were frequently well above the optimal value of one. It is also possible that the limited differences among treatments receiving fertilizer N reflect the high inherent variability in some of the measured parameters, particularly plant N accumulation. For example, plant N accumulation would need to differ between treatments by 15% over the 3-yr study to be statistically significant.

Previous studies on timing of fertilizer N application in eastern Canada and Maine also reported limited benefits from split N application compared with all N banded at planting with respect to tuber yield or crop N uptake (Porter and Sisson 1993; Zebarth and Milburn 2003; Zebarth et al. 2004a, b). Similarly in Quebec, Giroux (1982) and Li et al. (1999) found little benefit to split N application whereas Cambouris et al. (2007) found maximum tuber yield with 38–66% of N applied at planting.

Previous studies on the use of CRF on sandy soils commonly found a benefit in terms of increased tuber yield (Zvomuya and Rosen 2001; Ziadi et al. 2011) or reduced NO_3^- leaching losses (Zvomuya et al. 2003; Wilson et al. 2009). Studies on use of PCU products in potato production have focused on situations where the risk of NO_3^- leaching is high, particularly on sandy soils under irrigated production. Potato crop response to PCU products under conditions where the risk of NO_3^- leaching is limited, as in this study in rain-fed production on medium-textured soils, has not previously been examined.

In this study, therefore, there was a clear crop response to N fertilization, but the choice of N fertility treatment had little effect on crop response. There was, however, some evidence of increased N availability associated with use of a PCU product as indicated by petiole NO_3^- concentration and NNI.

N_2O Emissions and Nitrate Exposure

In Atlantic Canada, N_2O emissions have been shown to be associated primarily with the process of denitrification. In laboratory incubations, approximately half of the N_2O emissions at 60% WFPS in the absence of carbon addition as plant residues were attributed to nitrification, whereas emissions were primarily attributed to denitrification following addition of plant residues or at higher water contents (Gillam et al. 2008). In field experiments, timing of N_2O was associated primarily with rainfall events and not with times of rapid nitrification of applied ammonium-based fertilizers, consistent with denitrification as the primary source of N_2O emissions (Burton et al. 2008, 2012). In this study, the form of applied N varied among N fertility treatments, and consequently would be expected to influence nitrification rates. Therefore, while differences in N form may have resulted in differences in N_2O associated with the nitrification process, it is likely that most emissions in the current study were associated with the denitrification process.

Key controlling factors for denitrification include availability of NO_3^- and organic carbon as well as soil aeration (Firestone and Davidson 1989). In this study, there was a strong positive relationship between N_2O emissions and NE in each year. The NE is a time-integrated index of the availability of NO_3^- for the denitrification process (Burton et al. 2008). This suggests that within a given year, NO_3^- availability is the primary factor influencing the magnitude of N_2O emissions. The N fertility treatments examined in this study would not be expected to influence carbon availability or soil aeration, and therefore it is logical for NO_3^- availability to be the primary factor influencing N_2O emissions. Similarly, previous studies reported that cumulative growing season N_2O emissions increased linearly with increasing NE within a given year in potato and barley crops in eastern Canada (Burton et al. 2008; Zebarth et al. 2008).

Although N_2O emissions were strongly related to NE in each year, the slope of the relationship varied among years. That is, the magnitude of emissions for a given value of NE varied among years. This likely reflects the role of other factors in influencing N_2O emissions. For example, N_2O emissions for a given value of NE were lower in 2008 than in 2009 or 2010, likely reflecting the below average rainfall in 2008, which presumably resulted in drier soil conditions and a reduced potential for denitrification to occur. At low values of NE, greater N_2O emissions occurred in 2010 than in 2009, perhaps because a large proportion of the emissions in 2010 occurred early in the growing season when soil NO_3^- concentrations had not yet been depleted by plant N uptake. Zebarth et al. (2008) also found the relationships between N_2O emissions and NE to vary among 3 yr under barley production, whereas Burton et al. (2008) found the relationship between N_2O emission and NE to be the same across two years under potato production.

The relationships between cumulative N_2O emissions and NE were consistent across row locations. In this study, N_2O emissions were not different between the ridge and furrow in the unfertilized control treatment, and greater in the ridge than the furrow for N fertilized treatments. This presumably reflects the greater NO_3^- availability in the ridge as a result of fertilizer banding. Previous studies have also reported greater N_2O emission from the ridge than the furrow in studies where fertilizer was banded in the ridge (Burton et al. 2008; Dandie et al. 2008) but greater emissions in the furrow than the ridge in studies where fertilizer N was broadcast (Ruser et al. 1998).

In this study, the N fertility treatments influenced N_2O emissions primarily through their effect on soil NO_3^- availability as measured by NE. Application of fertilizer N increased N_2O emissions, and the increase was in proportion to the increase in NE. This is consistent with most studies, which report an increase in N_2O emissions with increasing N rate (Ruser et al. 2001).

In Atlantic Canada, under conventional fertilizer management, there is a period of up to 50 d between the time of fertilizer N application and planting and the time of rapid crop N uptake (Zebarth and Milburn 2003). It was expected that the split N application would reduce soil NO_3^- concentrations during the period between planting and the time rapid plant N uptake, and consequently reduce NE. Split N application did decrease NE relative to the conventional treatment, and this effect was consistent across all 3 yr of the study. This reduction in NE resulted in a numeric reduction in N_2O emissions compared with the conventional treatment, but this reduction was not statistically significant. Burton et al. (2008) found split N application to reduce N_2O emissions compared with all N applied at planting only in a year when wet spring conditions resulted in most N_2O emissions occurring between planting and split N application.

Similarly, it was also expected that the PCU treatment would reduce NE by better matching soil NO_3^- availability with plant N demand, thereby reducing soil NO_3^- accumulation and subsequently reducing N_2O emissions. However, use of PCU did not result in a significant decrease in NE, but rather resulted in numerically higher values of NE in 2009. Similarly, the PCU treatment did not result in reduced N_2O emissions, but rather resulted in numerically higher N_2O emissions, particularly in 2009, and higher N_2O emissions compared with split N application. This may reflect a somewhat higher efficiency (i.e., lower N losses and/or higher plant availability) of the PCU fertilizer compared with conventional fertilizer products; the PCU treatment had higher petiole NO_3^- concentration compared with the conventional treatment in 2009 and higher NNI than the split N treatment over the 3 yr of the experiment. Hyatt et al. (2010) reported that use of PCU reduced N_2O emissions compared with split N applications; however, this study was done in irrigated potato production on sandy soils. It may be that application of PCU fertilizer products at the same rate as conventional fertilizer products may actually increase the risk of N_2O

emissions because increased efficiency of the fertilizer results in higher soil NO_3^- concentrations.

This study evaluated the use of a PCU product compared with conventional fertilizer products banded all at planting or as a split application in rain-fed potato production in eastern Canada. It was expected that both split N application and the use of PCU would reduce the time period over which high NO_3^- concentrations were present in the soil, and consequently reduce the risk of N_2O emissions. Split N application did significantly reduce the availability of NO_3^- for the denitrification process, as indicated by a significant reduction in NE. In contrast, use of PCU did not reduce NE, but rather resulted in a numeric increase in NE and in N_2O emissions, when applied at the same rate as the conventional fertilizer product. This suggests that substitution of conventional fertilizer products with a PCU product will not necessarily reduce N_2O emissions, and may in some cases increase the risk of N_2O emissions. It may be necessary to reduce applications rates with PCU products in order to achieve benefits in terms of reduced N_2O emissions.

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