Polymer-Coated Urea Maintains Potato Yields and Reduces Nitrous Oxide Emissions in a Minnesota Loamy Sand

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Irrigated potato (*Solanum tuberosum* L.) production requires large inputs of N, and therefore has high potential for N loss including emissions of N_2O. Two strategies for reducing N loss include split applications of conventional fertilizers, and single applications of polymer-coated urea (PCU), both of which aim to better match the timing of N availability with plant demand. The objective of this 3-yr study was to compare N_2O emissions and potato yields following a conventional split application (CSA) using multiple additions of soluble fertilizers with single preplant applications of two different PCUs (PCU-1 and PCU-2) in a loamy sand in Minnesota. Each treatment received 270 kg of fertilizer N ha^{-1} per season. An unfertilized control treatment was included in 2 of 3 yr. Tuber yields did not vary among fertilizer treatments, but N_2O emissions were significantly higher with CSA than PCU-1. During 3 consecutive yr, mean growing season emissions were 1.36, 0.83, and 1.13 kg N_2O-N ha^{-1} with CSA, PCU-1, and PCU-2, respectively, compared with emissions of 0.79 and 0.42 kg N_2O-N ha^{-1} in the control. The PCU-1 released N more slowly during in situ incubation than PCU-2, although differences in N_2O emitted by the two PCUs were not generally significant. Fertilizer-induced emissions were relatively low, ranging from 0.10 to 0.15% of applied N with PCU-1 up to 0.25 to 0.49% with CSA. These results show that N application strategies utilizing PCUs can maintain yields, reduce costs associated with split applications, and also reduce N_2O emissions.

Abbreviations: AN, ammonium nitrate; BMP, best management practice; CSA, conventional split application; PCU, polymer-coated urea.

Potato production requires significant inputs of fertilizer N to optimize tuber yield and quality. Due to its shallow main rooting system when irrigated, potato is relatively inefficient in capturing applied N. In Minnesota, best management practices (BMPs) for late-season cultivars of irrigated potato in coarse-textured soils recommend application of up to 260 to 280 kg ha^{-1} N to optimize yields (Rosen and Bierman, 2008). Using mass balance analysis, Errebhi et al. (1998) found that only 33 to 56% of applied fertilizer N was recovered by a potato crop in an irrigated coarse-textured soil.

Applied fertilizer N can be transformed via nitrification, denitrification, and other processes to N_2O (Firestone and Davidson, 1989). Relative to other soil types, coarse-textured soils may not promote high rates of denitrification-driven N_2O loss; however, the high rates of N application required for potato production and the possibility of nitrification-driven N_2O production (Venterea, 2007) increase the potential for N_2O losses. Nitrous oxide is a greenhouse gas of growing concern, with a global warming potential 300 times greater than CO_2 (Forster et al., 2007). Global atmospheric N_2O concentrations are rising at approximately 0.26% yr^{-1} (Forster et al., 2007). Within the United States, 72% of anthropogenic N_2O emissions originate from agricultural practices (USEPA, 2008).

Mention of product names is for the convenience of the reader and implies no endorsement on the part of the authors or the USDA.
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One strategy for minimizing N_2O emissions, as well as other N losses, is the use of split applications of fertilizer distributed during the course of the growing season. The BMPs for potato production in Minnesota recommend split applications (Rosen and Bierman, 2008). Split applications of conventional N fertilizer have previously shown promise in reducing N_2O emissions from fields planted to potato (Burton et al., 2008). While this practice may conserve fertilizer N and protect environmental quality, it requires the time and expense associated with additional field applications. An alternative to split applications is the use of PCU products, which are designed to release N gradually during the growing season while requiring fewer or only one application. In theory, both techniques better synchronize the timing of N availability with plant demand. In addition to any environmental benefits, the impact of these practices on crop yields must also be considered in evaluating their potential for adoption.

The effects of PCU products on N_2O emissions have been examined for a variety of applications (e.g., Delgado and Mosier, 1996; Cheng et al., 2006; Halvorson et al., 2008, 2010). Previous studies have examined PCU effects on potato yields and N use efficiency with promising results (Shoji et al., 2001; Zvomuya et al., 2003; Hutchinson et al., 2003). A number of studies have examined N_2O emissions in potato as affected by conventional fertilizer management, tillage, and soil properties (Ruser et al., 2006; Vallejo et al., 2006; Burton et al., 2008; Haile-Mariam et al., 2008). To our knowledge, however, there are no studies examining N_2O emissions with PCUs for potato production. There are also no studies in any cropping system comparing N_2O emissions following multiple (i.e., more than two) split applications of conventional fertilizers vs. a single PCU application.

The objective of the current study was to compare N_2O emissions and crop yields under alternative N management systems including a CSA, similar to recommended BMPs, and single preplant applications of two different PCUs for irrigated potato production in Minnesota. Additional measurements were made to compare the rate of N release in the two PCU products during in situ incubation.

Table 1. Selected chemical properties of site soils. Samples were collected before establishing treatments (in April of each year) from the upper 0.15 m, except for inorganic N samples, which were collected from the upper 0.6 m. Methods of analysis from Brown (1998). Means with standard errors in parentheses are shown (n = 2–5).

Property	2007	2008	2009
pH	6.7 (0.04)	6.2 (0.13)	4.9 (0.03)
Organic matter, % (w/w)	1.5 (0.07)	2.0 (0.03)	2.4 (0.03)
Bray-P, mg kg^{-1}	32 (2.3)	32 (1.9)	23 (1.9)
K, mg kg^{-1}	88 (7.0)	110 (2.0)	66 (2.6)
SO_4, mg kg^{-1}	not done	2.0 (0)†	5.0 (1.0)
B, mg kg^{-1}	0.20 (0)†	0.21 (0.01)	0.28 (0.01)
Ca, mg kg^{-1}	720 (49)	810 (6.0)	335 (65)
Mg, mg kg^{-1}	140 (9.0)	140 (2.0)	40 (5.5)
Zn, mg kg^{-1}	0.67 (0.03)	0.70 (0)†	1.35 (0.05)
Fe, mg kg^{-1}	19 (0.70)	29 (0.20)	114 (9.90)
Cu, mg kg^{-1}	0.30 (0.04)	0.41 (0.01)	0.50 (0)†
Mn, mg kg^{-1}	4.9 (0.17)	7.2 (0.05)	37.6 (4.25)
NH_4^+–N, mg kg^{-1}	1.8 (0.10)	2.5 (0.39)	1.6 (0.13)
NO_3^-–N, mg kg^{-1}	1.3 (0.11)	2.2 (0.14)	1.4 (0.09)

† All replicates had the same result.

MATERIALS AND METHODS

Site Description and Experimental Design

The study was conducted during the 2007, 2008, and 2009 growing seasons (approximately 1 May–30 September) at the University of Minnesota's Sand Plain Research Farm in Becker, MN (45°23′N, 93°53′W). Soils at the site are a uniform Hubbard loamy sand (a sandy, mixed, frigid Entic Hapludoll) comprised of 82% sand, 10% silt, and 8% clay. Additional soil properties are shown in Table 1. The 30-yr average annual temperature and precipitation at the site are 6.8°C and 752 mm, respectively; 30-yr average temperature and precipitation during May through September are 18.7°C and 479 mm, respectively (Minnesota Climatology Working Group, 2009). A weather station was positioned on-site to measure air temperature and precipitation at 10-min intervals.

Experiments were conducted in a different section of the farm each year. The fields used for experiments in 2007 and 2009 were planted to unirrigated, unfertilized rye (*Secale cereal* L.) during the previous year. The field used in 2008 was planted in the previous year to rye followed by mustard [*Brassica juncea* (L.) Czern. and *Sinapis alba* L. blend], which was fertilized with 34 kg N ha^{-1} as NH_4NO_3 (AN). The rye grain was harvested in the summer; the rye stover and the 2007 mustard crop were disk incorporated in the fall. Each spring, N fertilizer treatments were established in a randomized complete block design, with three replications of each treatment. Plots were between 3.7 and 4.6 m wide and 6.1 m long. One week before planting in all years, 280 kg ha^{-1} of K–Mg sulfate and 280 kg ha^{-1} of KCl were broadcast and incorporated with a moldboard plow in all plots. On 26 Apr. 2007, 29 Apr. 2008, and 28 Apr. 2009, plots were hand planted with four rows of 'Russet Burbank' whole "B" seed potato with 0.9-m row spacing and 0.3-m seed spacing. For all but the control plots, a preweighed starter fertilizer containing 45 kg N ha^{-1} and 50 kg of P ha^{-1} as diammonium phosphate (DAP), 186 kg K ha^{-1}, 34 kg Mg ha^{-1}, 67 kg S ha^{-1}, 2.25 kg Zn ha^{-1}, and 0.6 kg B ha^{-1} was banded at planting 0.05 m below and 0.08 m to both sides of the row. Control plots received a similar mix that excluded DAP and substituted triple superphosphate.

Nitrogen fertilizer treatments included a CSA and two different PCU treatments that used a single preplant application, with all treatments receiving a total of 270 kg N ha^{-1} (including the DAP). In 2008 and 2009, an unfertilized control treatment was also examined. A summary of the treatments including the form, timing, and rates of N fertilizer application in each treatment is given in Table 2. In the CSA treatment, granular urea was surface banded at plant emergence on both sides of the row at 112 kg N ha^{-1}. Within 24 h of urea application, the rows were hilled in all treatments (on 15 May 2007, 28 May 2008, and 22 May 2009). Hilling also served to incorporate urea mainly within the hill area. In 2008, an equipment malfunction required all plots to be hilled a second time. Post-emergence fertilizer applications in the CSA treatment were broadcast by hand as 50% granular urea and 50% granular AN evenly over the entire plot (Table 2). This blend was then watered in with overhead irrigation to simulate fertigation with 28% urea–AN, which is a common practice in the area and consistent with BMP recommendations (Zvomuya et al., 2003; Rosen and Bierman, 2008). Post-emergence fertilizer applications started 2 to 3 wk after hilling and were repeated at intervals of 9 to 15 d (actual application dates are reported below).

In both PCU treatments, the material was broadcast 1 to 6 d before planting and mechanically incorporated via disking within 24 h of application. One of the PCU treatments (referred to as PCU-1, 42% N w/w) used a product manufactured by Shandong Kingenta Ecological Engineering Co. Ltd. (Linshu, China). The other PCU treatment (PCU-2, 44% N w/w) used a product (Environmentally Smart Nitrogen) manufactured by Agrium Inc. (Calgary, AB, Canada). The PCU-1 product was obtained directly from the manufacturer. In 2007, PCU-2 was obtained from the manufacturer, while in 2008 and 2009 the product was obtained from a local distributor. Irrigation water was applied through an Al pipe solid-set overhead sprinkler system. Irrigations were scheduled through the checkbook method as described in Wright (2002). The potato was mechanically harvested from the two inner rows of each plot on 28 Sept. 2007, 16 Sept. 2008, and 21 Sept. 2009. Tubers were graded and the mass of all tubers >113 g were tallied for marketable yield, expressed in megagrams per hectare.

Table 2. Timing and rate of fertilizer applications for conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and control treatments.

Treatment	Preplanting	Planting†	Emergence‡	Post-emergence§	Total¶
	kg N ha^{-1}				
			2007		
CSA	0	45	112	5 × 22.5	270
PCU-1	225	45	0	0	270
PCU-2	225	45	0	0	270
			2008 and 2009		
CSA	0	45	112	4 × 28	270
PCU-1	225	45	0	0	270
PCU-2	225	45	0	0	270
Control	0	0	0	0	0

† All fertilized treatments received 45 kg N ha^{-1} starter as diammonium phosphate.

‡ Emergence applications consisted of 100% urea.

§ Post-emergence applications consisted of 50% urea and 50% NH_4NO_3.

¶ All treatments received additional inputs equivalent to 34, 33, and 24 kg N ha^{-1} in 2007, 2008, and 2009, respectively, from NO_3 contained in irrigation water.

Nitrous Oxide Fluxes

Nitrous oxide flux between the soil and atmosphere was measured using cylindrical (0.22 m i.d. by 0.15 m deep) stainless steel chambers. The chambers were insulated with a surface-applied reflective insulation (Reflectix, Markleville, IN) and equipped with vent tubes, sampling ports with butyl rubber septa, and sharpened bottom edges following Venterea and Rolston (2000). The chambers were inserted directly into the soil before sampling. One chamber was positioned on the hill, while its twin was positioned in the furrow within 2 m of the hill location. Chamber locations within each plot were randomly selected on each sampling date.

The chamber insertion depth was kept to 0.02 m, since later in the season tubers can extend to within 0.02 m of the surface. It is known that a shorter chamber insertion depth can underestimate actual emissions; it is also suspected that making measurements immediately after chamber insertion may cause increased fluxes due to soil disturbance (Hutchinson and Livingston, 2002). To address these concerns, in an adjacent field planted to corn (*Zea mays* L.), we compared this chamber method to a fixed-anchor chamber method with an insertion depth of 0.08 m and found no significant difference in N_2O flux based on paired *t*-test analysis of 16 chamber locations.

Gas samples were collected via a 12-mL polypropylene (Monoject) syringe 0, 30, and 60 min after chamber insertion, as described in Venterea et al. (2005), and transferred to 9-mL glass autosampler vials sealed with butyl rubber septa and Al caps (Alltech, Deerfield, IL). Gas flux samples were collected at least weekly from 27 Apr. through 14 Sept. 2007, 1 May through 28 Sept. 2008 (with an additional sampling on 20 Oct. 2008), and 1 May through 14 Sept. 2009. For nearly the entire 2009 season, and during 15 May to 15 June 2007 and 20 May to 25 August 2008, sampling was performed twice per week. Fluxes were measured on a total of 25, 35, and 36 dates in 2007, 2008, and 2009, respectively.

Gas samples were stored at room temperature until analysis, which was done within 3 d of collection. Analysis of N_2O was performed on a gas chromatograph (Model 5890, Hewlett-Packard/Agilent, Palo Alto, CA) equipped with an electron capture detector. The gas chromatograph was connected to a headspace autosampler (Teledyne Tekmar, Mason, OH). The system was calibrated daily using a set of analytical-grade standards (Scott Specialty Gases, Plumsteadville, PA). After converting N_2O mixing ratios (ppm) to concentration units (μg N m^{-3}) using the ideal gas law and the air temperature at the time of sampling, gas fluxes were calculated using quadratic regression of the chamber concentration data vs. time (Wagner et al., 1997), multiplying the slope at time zero by the chamber volume, and dividing by the soil surface area.

Soil Sampling and Analysis

Samples for soil moisture content determination were collected within 1 h of gas flux sampling using an 18-mm-diameter core sampler to a depth of 0.1 m in three randomly selected locations within the furrow of each plot. The samples were oven dried at 105°C for 24 h. Core samples were also taken to determine bulk density once per season. The soil temperature was measured during gas sampling using temperature probes (Fisher, Hampton, NH) inserted 0.05 m deep in the furrow area within 1 m of each chamber.

Nitrogen Fertilizer Release

The rates of N release from the two PCU products during the 2007 and 2008 growing seasons were examined in in situ incubation of fertilizer granules using a weight-loss method described by Wilson et al. (2009). Samples of each product (3 ± 0.0002 g) were placed in 0.1-m^2 polypropylene bags (Industrial Netting, Minneapolis, MN) with 1.2-mm^2 mesh size. Bags were heat sealed and buried to a depth of 0.05 to 0.10 m. The initial bag placement occurred on the same day as fertilizer application (1–6 d before planting). Bags were removed during hilling and then reburied within the hill. Three sets of 10 bags for each of the two PCUs were buried in three plots that had been fertilized with the respective PCU. A single bag was removed from each plot for testing at approximately 2-wk intervals until after harvest. In the laboratory, the bags were placed inside paper bags and air dried for at least 2 wk. Any attached soil was removed from the granules, which were then weighed to determine the mass of N released (Wilson et al., 2009). Empirical functions describing N release as a function of time were obtained using nonlinear regression (SigmaPlot version 10.0, Systat, Chicago, IL).

Data Analysis and Statistics

To determine the total daily N_2O flux for each plot, fluxes from the hill and furrow locations were averaged because the hill and furrow sections each represented approximately 50% of the plot area. Daily flux was compared to the soil moisture and temperature via simple and multiple linear regression using Statgraphics Plus 5.1 (Statistical Graphics Corp., Warrenton, VA). Cumulative flux between successive sampling dates was determined by multiplying the average daily flux of the two sampling dates by the time elapsed between events (i.e., trapezoidal integration). These values were summed to determine cumulative seasonal emissions. Analysis of variance in all cases was performed using the general linear model (GLM) procedure in SAS (SAS Institute, 2003). The effects of fertilizer treatment on daily fluxes from the hill and furrow locations, and their daily means, were examined using split-plot ANOVA, with fertilizer type as the main effect and date as the split-plot effect. The effects of fertilizer treatment on the total cumulative emissions and tuber yields were analyzed using one-way ANOVA separately for each growing season. The effects of fertilizer treatment on the total cumulative emissions and tuber yields throughout the entire study were analyzed using split-plot ANOVA, with fertilizer type as the main effect and year as the split-plot effect. Unless indicated otherwise, significant differences used a criterion of $P < 0.05$. For 2008 and 2009, fertilizer-induced N_2O emissions in each fertilized treatment were determined by subtracting the mean cumulative emissions observed in the control treatment from the mean cumulative emissions in the fertilized treatment, expressed as a percentage of the fertilizer N inputs (i.e., 270 kg N ha^{-1}).

RESULTS

Weather

Water inputs during the period 1 May through the date of harvest each season are shown in Fig. 1c, 2c, and 3c. The second year of the study (2008) was relatively normal with respect to growing-season rainfall, while 2007 and 2009 were drier than normal. Precipitation amounts during May through September in 2007, 2008, and 2009 were approximately 85, 95, and 67%, respectively, of the 30-yr average (479 mm). Total water inputs (including irrigation) were similar each year (745–896 mm). Due to higher precipitation in 2008, a lower proportion of total inputs in 2008 were from irrigation (i.e., 44%) compared with 2007 (55%) and 2009 (57%).

With the exception of an early-season spike to nearly 0.35 kg H_2O kg^{-1} on 18 May 2007, soil moisture remained between 0.08 and 0.16 kg H_2O kg^{-1} soil (Fig. 1c, 2c, and 3c). Based on an average measured soil bulk density of 1.1 g cm^{-3}, this range of water content values corresponds to a range in water-filled pore space of 15 to 30% (66% on 18 May 2007). Average soil and air temperatures during the 2007 growing season were slightly higher than in 2008 and 2009 (Fig. 1d, 2d, and 3d), with no significant differences in water content or temperature between treatments. Mean daily air temperatures during the 2007, 2008, and 2009 growing season were 19.6, 18.4, and 18.1°C, respectively, compared with a 30-yr average of 18.7°C.

Nitrous Oxide Emissions

In 2007, the maximum N_2O fluxes occurred in the hill chamber positions across all treatments (Fig. 1a and 1b). In the 6-wk period following urea application on 15 May 2007, mean fluxes from the hill positions in the CSA treatment peaked to nearly 300 μg N m^{-2} h^{-1} (on 12 June) before decreasing to baseline levels. The PCU-2 treatment also displayed increased emissions from hill positions during the same period, despite no post-plant application. Increased fluxes during this period coincided with a 25-mm rainfall event on 29 May and soil temperatures >25°C. Following the third post-emergence fertilizer application (on 2 July), mean N_2O fluxes remained below 30 μg N m^{-2} h^{-1} for the remainder of the season.

In contrast to 2007 and 2009, maximum N_2O fluxes in 2008 occurred in the furrow positions (Fig. 2a and 2b). The CSA treatment displayed several episodes of increased fluxes (>150 μg N m^{-2} h^{-1}) in both hill and furrow positions, some of which may have been responses to post-emergence fertilizer applications and large rain events. A 48-mm rain event on 11 June was followed by large but short-lived increases in fluxes (>300 μg N m^{-2} h^{-1}) from the furrow chamber positions in the CSA and PCU-2 treatments (Fig. 2a).

In 2009, mean fluxes remained ≤80 μg N m^{-2} h^{-1} for the entire season in all treatments, with the exception of a single sampling date (Fig. 3a and 3b). On 13 August, the mean fluxes in the furrow position of the CSA and PCU-2 treatment were >400 μg N m^{-2} h^{-1}, compared with 180 and 80 μg N m^{-2} h^{-1} in the PCU-1 and control treatments, respectively. Soil water content in the upper 0 to 10 cm and temperature at the 5-cm depth were at or near their maximum values of the season on this date. Further analysis of the water input data indicated that cumulative water inputs calculated during the previous 10 d were also close to the maximum value at this time. Thus, it is possible that the observed spike in N_2O flux was due to high soil water content (including depths below 10 cm due to high cumulative water inputs) coinciding with high soil temperature.

The results of statistical analysis of the daily flux data are shown in Table 3. In 2007 and 2008, the mean daily fluxes from the hill position were higher in the CSA treatment than the two PCU treatments, while differences in the furrow position fluxes were not significant. In 2009, daily fluxes in the furrow position in the CSA treatment were higher than in PCU-1. After averaging hill and furrow data, fluxes from the CSA treatment were higher (at $P < 0.10$) than PCU-1 in 2008 and both PCU treatments in 2007 and 2009. Combined daily fluxes from the control were lower than CSA and PCU-2 in 2008 and lower than all fertilized treatments in 2009.

Cumulative N_2O emissions during each growing season ranged from 0.6 to 2.1 kg N ha^{-1} in the fertilized treatments (Fig. 4a). Mean emissions from the control treatment were nearly twice as high in 2008 (0.79 kg N ha^{-1}) as in 2009 (0.42 kg N ha^{-1}), although this difference was not significant ($P > 0.10$). During individual growing seasons, the only significant differences (at $P <$ 0.10) were that cumulative emissions from CSA were higher than PCU-1 in 2007, and higher than the control in 2008 and 2009. During the entire study, however, emissions from CSA were significantly higher than from PCU-1, while emissions from PCU-2 did not differ from CSA or PCU-1.

In 2008, fertilizer-induced N_2O emissions were equivalent to 0.49, 0.10, and 0.39% of N inputs in the CSA, PCU-1, and PCU-2 treatments, respectively. In 2009, fertilizer-induced N_2O emissions were equivalent to 0.25, 0.15, and 0.16% of N inputs in the CSA, PCU-1, and PCU-2 treatments, respectively. Across all fertilized treatments, cumulative emissions were significantly higher in 2008 (1.67 kg N ha^{-1}) than in 2007 (0.73 kg N ha^{-1}) and 2009 (0.92 kg N ha^{-1}). Regression analysis found weak correlations between individual flux measurements and soil moisture or temperature ($r^2 \leq 0.2$) for the entire data set or when the data were segregated by treatment or year. There were no differences in tuber yields among the fertilized treatments (Fig. 4b). Yields were suppressed by approximately 28 and 46% in the control plots compared with the fertilized treatments in 2008 and 2009, respectively.

Nitrogen Release Rates

The cumulative mass of N released from the PCU products during in situ incubation was well described ($r^2 > 0.96$) by sigmoidal relationships in the form

$$N_R = N_0 + \frac{a}{1+\exp\left[-\left(t-t_0\right)/b\right]} \qquad [1]$$

where N_R is the cumulative N released (g N Kg^{-1} product), t is the time since bag placement, and N_0, t_0, a, and b are regression coefficients (Fig. 5a). Curves obtained using Eq. [1] were used to estimate the instantaneous release rates for each product via numerical differentiation (Fig. 5b). In both years, PCU-2 released N more quickly than PCU-1. On 21 May 2007, 10 d before the date of the first notable increase in N_2O flux from the PCU-2 treatment (Fig. 1b), the PCU-2 product in the mesh bags had lost 27% of its total N, compared with 18% lost by PCU-1. By 19 June 2007, 4 d after a second increase in N_2O flux, PCU-2 had lost 66% of its total N when PCU-1 had only lost 32% of its total N. In 2008, the difference between the PCUs was just as dramatic, with 26 and 65% loss by 2 June for PCU-1 and PCU-2, respectively. Both products released N at faster rates in 2008 than 2007. The maximum release rates, corresponding to the inflection points in Fig. 5b, were 2.9 and 3.5 g N kg^{-1} d^{-1} for PCU-1 in 2007 and 2008, respectively, compared with 6.8 and 8.3 g N kg^{-1} d^{-1} , respectively, for PCU-2.

DISCUSSION

As far as we know, this is the first study to compare N_2O emissions in potato fertilized with PCUs vs. conventional fertilizers, or to compare single, preplant applications of PCUs to multiple (i.e., more than two) split applications of conventional soluble fertilizers in any cropping system. The high N demand

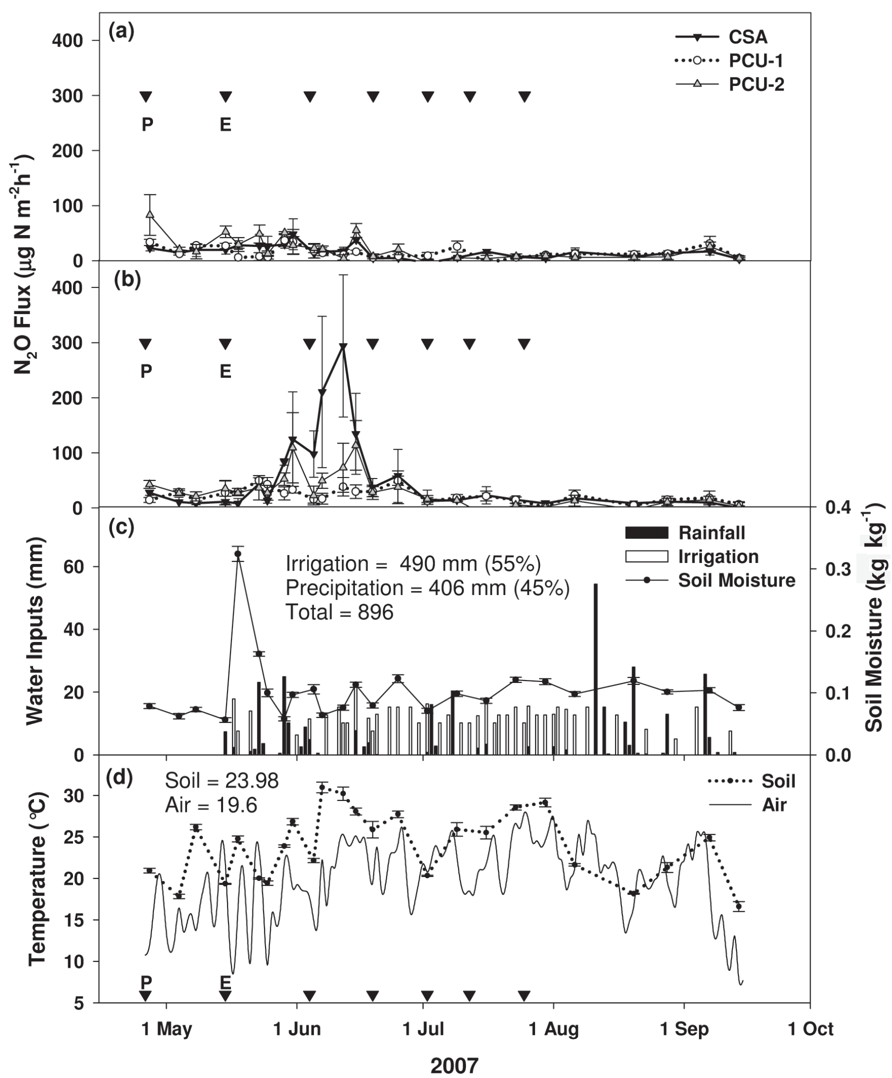

Fig. 1. Soil N_2O fluxes from the (a) hill and (b) furrow positions of potato fertilized using a conventional split application (CSA) and polymer-coated urea products (PCU-1 and PCU-2); (c) water inputs and soil moisture; and (d) soil and air temperatures during 2007. Arrows indicate timing of fertilizer applications with CSA, which occurred at planting (P), emergence (E), and five times after emergence. The PCUs were added in a single preplant application. Total seasonal precipitation and irrigation inputs are given in (c) as a percentage of total inputs, and seasonal mean soil and air temperatures are given in (d).

of potato presents a challenge for minimizing fertilizer N losses, particularly in coarse-textured soils. Growers recognize the need to strategically manage N under these conditions due to the high rates of N loss from leaching that have been observed (Errebhi et al., 1998; Delgado et al., 2001; Zvomuya et al., 2003). The lack of any negative yield impacts found here for PCUs demonstrates that, from a purely agronomic perspective, these products may afford potato growers the option to avoid the inconvenience of multiple split applications of urea or other conventional products.

Our results also indicate that N_2O emissions may be reduced, or at least maintained, with a single application of a PCU for potato production compared with multiple split applications of conventional fertilizers. One of the PCU products (PCU-1) resulted in significantly lower N_2O emissions than CSA during the entire study. Lower N_2O emissions following one-time applications of a PCU compared with uncoated urea have been observed in barley (*Hordeum vulgare* L.), Chinese cabbage [*Brassica rapa* L. ssp. *chinensis* (L.) Hanelt], and corn (Delgado and Mosier, 1996; Cheng et al., 2006; Halvorson et al., 2010). Polymer-coated ureas have also shown reduced emissions in corn when compared with two split urea applications (Yan et al., 2001; Hadi et al., 2008; Jumadi et al., 2008).

Polymer-coated ureas are designed to release N gradually during the growing season in response to moisture. Water passes by diffusion through pores in the polymer coating of the PCU granule, dissolving the urea, which then can diffuse back into the soil through the intact coating (Trenkel, 1997; Agrium Inc., 2009). Rupturing of the coating may occur, and increased temperature enhances the rate of N release (Shaviv, 2000). While several studies have compared N_2O emissions from PCU products vs. urea impregnated with nitrification and urease inhibitors (Delgado and Mosier, 1996; Hadi et al., 2008; Jumadi et al., 2008; Dobbie and Smith, 2003), direct comparisons between different types of PCUs are uncommon. In our study, N_2O emissions from the PCU-1 and PCU-2 treatments did not differ significantly throughout the entire study, but only PCU-1 had lower cumulative emissions than the CSA system. Additional statistical analysis of emissions data from the two seasons where a control treatment was used (2008 and 2009) indicated that emissions from PCU-1 did not vary from the control treatment and were significantly lower than both CSA and PCU-2. These trends may have been due in part to slower release of N from PCU-1 than PCU-2, as observed in the in situ incubation experiments. The lower N content of PCU-1 (42%) compared with PCU-2 (44%) indicates that PCU-1 contained a greater mass of polymer per mass of product (8.7%) compared with PCU-2 (4.3%). The higher mass of coating in PCU-1 may have resulted in a slower rate of N release. It is also possible that differences in the chemical composition of the coating materials may have contributed to different release rates. Polyurethane, polyolefin, and alkyd resins are all used as coatings by various PCU manufacturers (Trenkel, 1997).

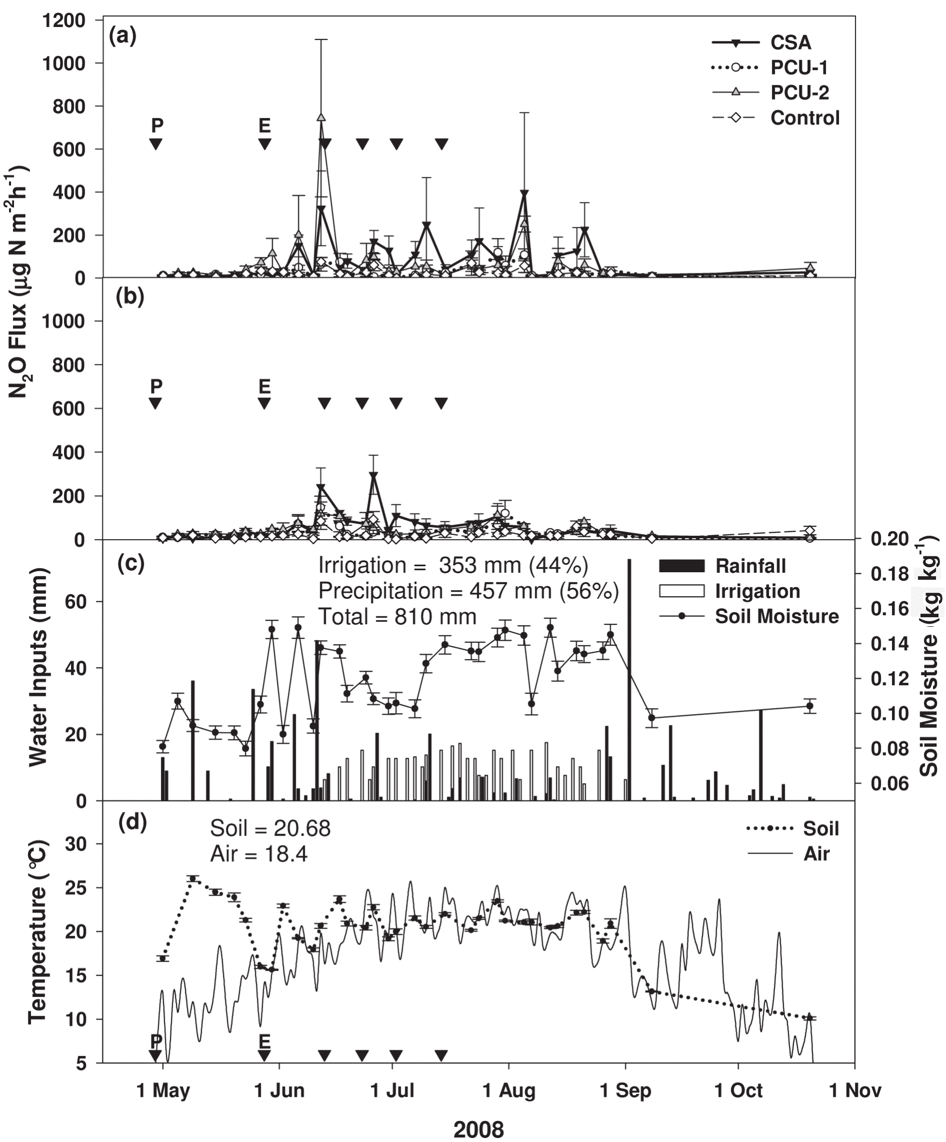

Fig. 2. Soil N_2O fluxes from the (a) hill and (b) furrow positions of potato fertilized using a conventional split application (CSA) and polymer-coated urea products (PCU-1 and PCU-2); (c) water inputs and soil moisture; and (d) soil and air temperatures during 2008. Arrows indicate timing of fertilizer applications with CSA, which occurred at planting (P), emergence (E) and four times after emergence. The PCUs were added in a single preplant application. Total seasonal precipitation and irrigation inputs are given in (c) as a percentage of total inputs, and seasonal mean soil and air temperatures are given in (d).

The bag-incubation method used here, which relied on the measurement of granule weight loss with time, compared favorably with bag incubation that used direct chemical analysis of granule N content with time (Wilson et al., 2009). The weight-loss method is presented primarily as an estimate of relative release rates, i.e., for comparison of different PCUs under the same conditions, or the same PCU under different conditions; however, incubation of granules in bags may not closely mimic the physical contact with soil particles and water experienced by the actual applied product. Wilson et al. (2009) showed that the hole size of the mesh bags influenced the release rate that was measured. We did use the bag type and hole size found by Wilson et al. (2009) to generate the highest release rates. Nonetheless, the absolute release rates measured in this study were probably less than actual release rates. A technique to determine N release that does not include a mesh bag has not been developed, however.

Averaged across all fertilized treatments, higher N_2O emissions were observed in the 2008 growing season than in 2007 or 2009. In situ release rates for both PCUs were also higher in 2008 than 2007. These trends may in part have been due to greater and more frequent rainfall in 2008. Rainfall events tended to introduce more water in a shorter time period than irrigation. In 2008, there were 10 rainfall events delivering >20 mm in a 24-h period, compared with six such events in 2007, and four events in 2009. In 2008, there were two events of ~35 mm before emergence, and two additional events of 26 and 48 mm within 2 wk after emergence. Total rainfall amounts occurring between planting and 1 wk following the final fertilizer application in the CSA treatment were 285 mm in 2008, and only 159 and 172 mm in 2007 and 2009, respectively. An increased frequency of significant rainfall during this period could have contributed to the multiple spikes in N_2O emissions observed (Fig. 2) by promoting the release of N from the PCUs and subsequently promoting N_2O production. The PCU-2 treatment, and to a lesser extent the PCU-1 and control treatments, displayed emission peaks that coincided with increased fluxes from the CSA treatment. This suggests that common factors such as soil moisture and temperature also played a role in stimulating N_2O production during these periods.

The higher emissions in 2008 cannot be definitively or solely attributed to the wetter conditions that year, however. The field used in 2008 was planted to rye and mustard and fertilized (34 kg N ha^{-1}) the previous year, whereas the fields used in 2007 and 2008 were preceded by unfertilized rye. While this did not show up as a large difference in preseason inorganic N or organic matter content (Table 1), it is possible that a greater mineralization of N occurred during the 2008 growing season due to a larger input of N-containing plant residues from the previous year. It is also possible that the combined effect of rainfall and site history was important.

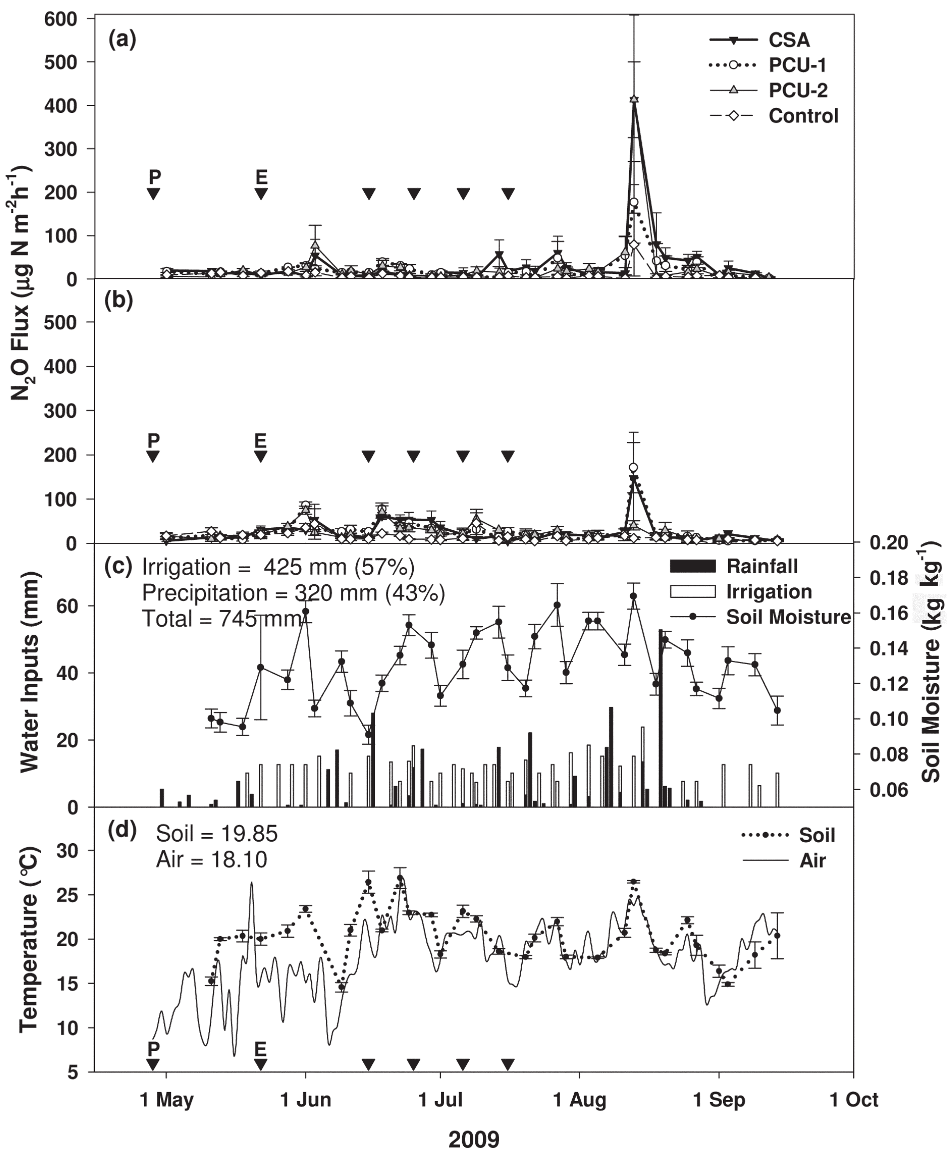

Fig. 3. Soil N_2O fluxes from the (a) hill and (b) furrow positions of potato fertilized using a conventional split application (CSA) and polymer-coated urea products (PCU-1 and PCU-2); (c) water inputs and soil moisture; and (d) soil and air temperatures during 2009. Arrows indicate timing of fertilizer applications with CSA, which occurred at planting (P), emergence (E) and four times after emergence. The PCUs were added in a single preplant application. Total seasonal precipitation and irrigation inputs are given in (c) as a percentage of total inputs, and seasonal mean soil and air temperatures are given in (d).

Table 3. Daily soil N_2O fluxes (mean and standard error in parentheses) in plots fertilized using conventional split application urea (CSA), polymer-coated urea (PCU) products, and unfertilized control. Within each column and year, values with the same letter are not significantly different; uppercase letters indicate $P < 0.05$, and lowercase letters indicate $P < 0.10$.

Treatment	Daily N_2O flux		
	Hill position	Furrow position	Combined†
	μg N m^{-2} h^{-1}		
		2007	
CSA	51.3 (11) B	16.6 (2.1)	33.9 (5.9) c
PCU-1	23.2 (2.1) A	16.2 (2.2)	19.7 (1.6) a
PCU-2	30.6 (5.0) A	21.8 (3.1)	26.3 (2.9) ab
		2008	
CSA	57.7 (7.3) C	69.7 (12)	63.7 (7.1) b
PCU-1	35.0 (3.9) B	28.8 (3.9)	31.9 (2.8) a
PCU-2	41.5 (3.9) B	67.6 (16)	54.6 (8.3) b
Control	22.0 (2.7) A	19.8 (2.7)	20.9 (1.9) a
		2009	
CSA	29.7	39.1 C	34.4 c
PCU-1	27.3	24.9 B	26.1 b
PCU-2	23.0	30.2 BC	26.6 b
Control	15.7	9.41 A	12.5 a

† Combined data were obtained by averaging hill and furrow data for each sampling date.

Since soil water-filled pore space was generally <30%, denitrification was probably not the predominant source of N_2O. Denitrification-generated N_2O requires nearly completely anaerobic soil conditions, while nitrifier-generated N_2O can proceed under fully aerobic conditions and is enhanced when the soil O_2 status is only partly reduced below ambient conditions (Venterea, 2007). Thus, nitrification was probably responsible for the majority of N_2O production in all three seasons. Similarly, Venterea et al. (2010) concluded that nitrification was the dominant source of N_2O in corn fertilized with anhydrous NH_3 and conventional urea in a well-drained silt loam in southeastern Minnesota.

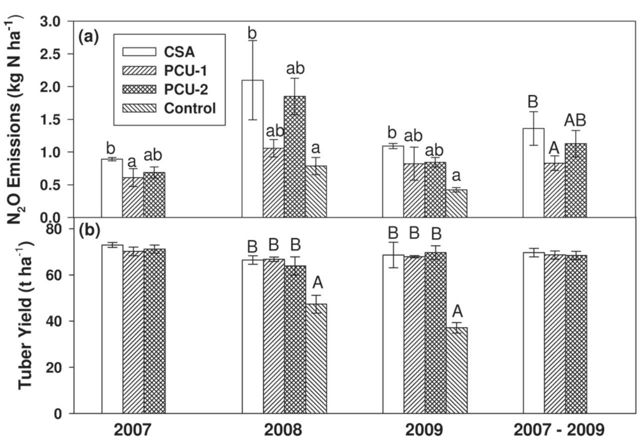

Fig. 4. (a) Total seasonal cumulative N_2O emissions and (b) marketable tuber yield in plots fertilized using a conventional split application (CSA), polymer-coated urea products (PCU-1 and PCU-2), and unfertilized control. Mean values with standard error bars are shown ($n = 3$). Values during the study period (2007–2009) are shown only for the fertilized treatments. Within each time period, bars with the same letter are not significantly different; uppercase letters indicate $P < 0.05$, lowercase letters indicate $P < 0.10$.

The temporal patterns in N_2O emissions observed during each growing season differed substantially across the 3 yr of the study, as did trends with respect to emissions from hill vs. furrow chamber positions (Fig. 1–3). In 2007, emissions were dominated by a large and prolonged response in the hill chamber position following the initial urea application. This pattern is similar to that found by Haile-Mariam et al. (2008), who also saw a higher flux from hills than furrows under urea–AN applied with center pivot irrigation, and to that observed by Burton et al. (2008) with band-applied AN. In 2008, there were multiple apparent responses to water inputs and fertilizer additions during June through September, primarily in the furrow and to a lesser extent in the hill. The spikes in emissions did not appear to correspond to application dates, in contrast to the results of Haile-Mariam et al. (2008), who observed a direct, almost one-to-one response between fertilizer application dates and N_2O emission spikes. Higher flux in the furrow position has been reported by others (Ruser et al., 1998; Smith et al., 1998) but these studies were conducted in finer textured soils where interrow compaction or higher water-filled pore space in the furrows may have contributed to higher N_2O emissions. In the current study, soil moisture samples were collected exclusively from the furrow position and differences in bulk density between hill and furrow locations were not measured, so we are unable to assess whether differences between hill and furrow were attributable to these factors. In 2009, fluxes were dominated primarily by one large spike in mid-August, mainly in the furrow. These results confirm the need for frequent flux sampling and also accounting for fluxes originating in different subsections of the interrow area to more accurately assess field-scale emissions.

We found no significant difference in marketable tuber yields with respect to fertilizer treatments. Zvomuya et al. (2003) observed occasional increases in potato yields in a loamy sand in Minnesota using a PCU compared with conventional fertilizers, particularly under conditions of high N leaching. They surmised that leaching reduced the N availability in fields amended with conventional fertilizers, resulting in increased N use efficiency and yields with the PCU. Worthington et al. (2007) found significantly higher potato yields in northeast Florida in a fine sandy soil with a coated urea compared with AN under a variety of leaching conditions. Pack et al. (2006) found, in another northeastern Florida fine sand, that potato yields following PCU applied at 146 kg N ha^{-1} were not significantly different compared with AN applied at 225 kg N ha^{-1}. These studies suggest that PCUs can reduce N leaching losses while maintaining, if not increasing, potato yields.

CONCLUSIONS

During 3 consecutive yr, the mean cumulative growing-season N_2O emissions were 1.36, 0.83, and 1.13 kg N ha^{-1} with a CSA and two different PCU products (PCU-1, and PCU-2), respectively. As expected in a very coarse-textured soil, these emissions represented only 0.1 to 0.5% of the applied fertilizer N after accounting for emissions from unfertilized control treatments. On an absolute scale, however, these emissions are comparable to rates measured in other cropping systems that require smaller N inputs. For example, in corn fertilized with single applications of 146 kg N ha^{-1} yr^{-1} with conventional urea on a silt loam in Minnesota, N_2O emissions ranged from 0.6 to 1.4 kg N ha^{-1} during three consecutive growing seasons (Venterea et al., 2010). Thus, the N_2O contribution from a high-N-input crop such as potato, even though it may be grown in a sandy soil, can be very comparable to that from other crops grown in finer textured soils.

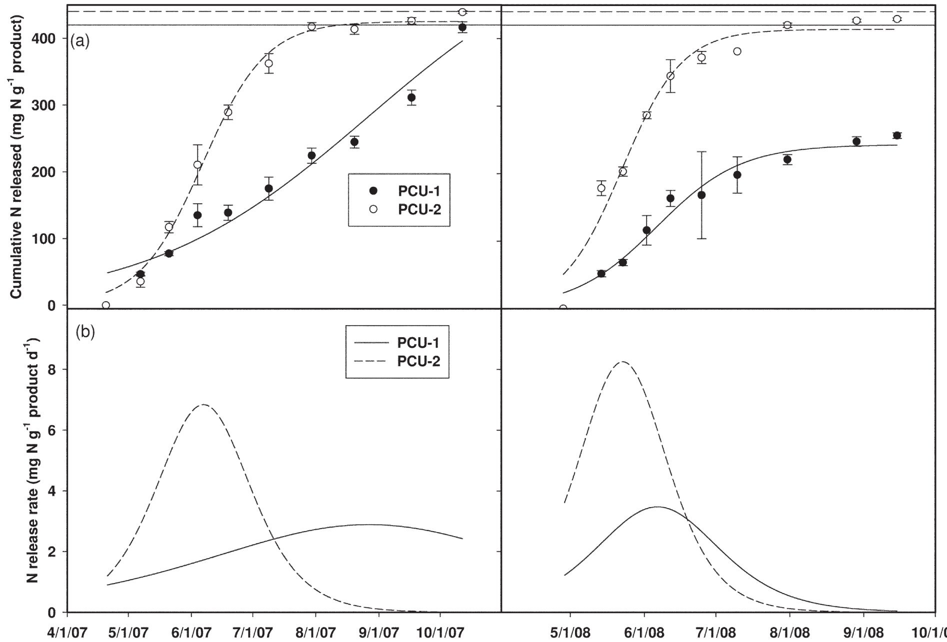

Fig. 5. (a) Cumulative mass of N released from polymer-coated urea products (PCU-1 and PCU-2) during in situ incubation and (b) corresponding N release rates during 2007 (left) and 2008 (right). Symbols are mean with standard error bars (*n* = 3). Curves in (a) were obtained by nonlinear regression using Eq. [1], and curves in (b) were obtained by numerical differentiation of the curves in (a). Incubation bags were installed 20 Apr. 2007 and 28 Apr. 2008. Horizontal lines in (a) represent maximum potential loss based on N content of PCU-1 (solid line) and PCU-2 (dashed line), i.e., 420 and 440 g N kg^{-1}, respectively.

These results show that N application strategies utilizing PCUs can maintain potato yields, reduce costs associated with split applications, and also reduce N_2O emissions. A PCU-based treatment can reduce equipment field time and personnel costs, but these must ultimately be weighed against the increased cost of the PCU products. An economic analysis is needed to determine what, if any, financial benefit PCU products provide. What is clear is that the environmental benefits combined with the potential economic benefits make coated urea fertilizers worth continued study, especially in high-value crops such as potato.

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