Ground Water Quality

Nitrate Leaching and Nitrogen Recovery Following Application of Polyolefin-Coated Urea to Potato

Francis Zvomuya, Carl J. Rosen,* Michael P. Russelle, and Satish C. Gupta

ABSTRACT

High N fertilizer and irrigation amounts applied to potato (*Solanum tuberosum* L.) on coarse-textured soils often result in nitrate (NO_3) leaching and low recovery of applied fertilizer N. This 3-yr study compared the effects of two rates (140 and 280 kg N ha^{-1}) of a single polyolefin-coated urea (PCU) application versus split applications of urea on 'Russet Burbank' potato yield and on NO_3 leaching and N recovery efficiency (RE) on a loamy sand. Standard irrigation was applied in all years and excessive irrigation was used in another experiment in the third year. At the recommended rate of 280 kg N ha^{-1}, NO_3 leaching during the growing season was 34 to 49% lower with PCU than three applications of urea. Under standard irrigation in the third year, leaching from five applications of urea (280 kg N ha^{-1}) was 38% higher than PCU. Under leaching conditions in the first year ($\geq$25 mm drainage water in at least one 24-h period) and excessive irrigation in the third year, PCU at 280 kg N ha^{-1} improved total and marketable tuber yields by 12 to 19% compared with three applications of urea. Fertilizer N RE estimated by the difference and ^{15}N isotope methods at the 280 kg N ha^{-1} rate was, on average, higher with PCU (mean 50%) than urea (mean 43%). Fertilizer N RE values estimated by the isotope method (mean 51%) were greater than those estimated by the difference method (mean 47%). Results from this study indicate that PCU can reduce leaching and improve N recovery and tuber yield during seasons with high leaching.

Potato has a high N requirement, but its recovery of fertilizer N is often quite low. The low efficiency is partly due to a shallow root system that is usually confined to the top 60 cm of soil, with 90% of the root length in the surface 25 cm of the soil profile (Tanner et al., 1982). Coarse-textured soils on which potato is commonly grown have low water holding capacity and high water conductivity, thus necessitating irrigation to meet water demand of the crop, and increasing the likelihood of NO_3 leaching. To obtain high optimal yield, high rates of N are often applied. These plant, soil, and management factors, together with unpredictable rainfall events during the growing season, often result in low N RE by the crop and large NO_3 leaching losses.

Twelve percent of public wells in major potato-growing counties in Minnesota during 1997–1998 were above the USEPA 10 mg L^{-1} limit for NO_3–N (Gallus and Montgomery, 1998). Elevated NO_3 levels have also been measured in ground water sources adjacent to potato fields in Wisconsin (Saffigna and Keeney, 1977) and southern Ontario, Canada (Hill, 1986). In Quebec, NO_3–N concentrations of up to 40 mg L^{-1} have been measured in subsurface water draining from a sandy field cropped to potato (Madramootoo et al., 1992). Mass balance data from the study by Hill (1986) indicated that 78 to 220 kg N ha^{-1} was lost annually below 183 cm under potato crops receiving 160 to 210 kg N ha^{-1} annually.

Nitrate accumulation in the soil and leaching out of the root zone are determined by, among other things, the amount of N applied relative to crop demand and removal. Nitrate leaching can therefore be minimized by either reducing N fertilizer rates or increasing the proportion of applied N removed in the harvested portion of the crop. Nitrogen loss from fertilizer applications results in lower N RE in crop production. Conversely, low recovery of applied N by the crop can augment N loss to the environment. Results from a study by Gerwing et al. (1979) in central Minnesota confirmed that maintaining high N RE would minimize the amount of N subject to leaching. In potato production, fertilizer N recoveries commonly range between 30 and 70% (Hill, 1986; Errebhi et al., 1998; Meyer and Marcum, 1998).

Past potato fertility research on irrigated sandy soils has focused mainly on irrigation management and N fertilizer rates, placement, and timing (Errebhi et al., 1998; Waddell et al., 2000). However, even with properly timed season-long N management and appropriate irrigation plans, controlling NO_3 leaching is difficult due to unforeseen rainfall events immediately following irrigation or N application (Sexton et al., 1996). Therefore, more effective alternative approaches to reduce NO_3 loss to ground water are needed.

Controlled-release fertilizers (CRFs) may be one such alternative that may improve N recovery by the crop, thereby minimizing excessive NO_3 leaching. Nitrogen release from traditional products, such as sulfur-coated urea, has been unpredictable (Trenkel, 1997). Recently, improved CRFs have been developed with polymer coating technology to modify the rate and duration of nutrient release. Polymer-coated CRFs can improve N use efficiency in corn (*Zea mays* L.) (Shoji et al., 1991) and decrease NO_3 leaching (Wang and Alva, 1996). Zvomuya and Rosen (2001) reported higher potato yields for PCU compared with urea, but effects on N leaching and N RE were not evaluated.

The objectives of this study were to (i) investigate the efficacy of PCU as a tool in minimizing NO_3 leaching and improving N RE in potato and (ii) characterize the fate of PCU- and urea-N applied to irrigated potatoes.

MATERIALS AND METHODS

Four experiments were conducted in a different field each year from 1997 through 1999 at the Sand Plain Research Farm

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Published in J. Environ. Qual. 32:480–489 (2003).

Abbreviations: CRF, controlled-release fertilizer; DAP, days after planting; PCU, polyolefin-coated urea; RE, recovery efficiency.

in Becker, Minnesota. The soil at the site is an excessively drained Hubbard loamy sand (sandy, mixed, frigid Entic Hapludoll) formed in sandy glacial outwash. Depth to the water table is typically 2 m or more. The previous crop was nonirrigated rye (*Secale cereale* L.) in 1997 and 1998 and soybean [*Glycine max* (L.) Merr.] in 1999. Before treatment establishment in spring, soil samples were collected from the surface 15 cm for routine analysis, and from the top 60 cm for determination of residual NO_3–N according to the methods described by Rosen and Eliason (1996) (NH_4–N was negligible, i.e., <1 kg ha^{-1} in all experiments). Soil pH before planting for the three years ranged from 6.5 to 6.7, organic matter was 1.7 to 1.9%, Bray P1 was 29 to 54 mg P kg^{-1}, and ammonium acetate–extractable K was 107 to 144 mg kg^{-1}.

Before planting, the experimental area received broadcast applications of 225 kg ha^{-1} potassium chloride and the same rate of potassium–magnesium sulfate, which were immediately incorporated. Triple superphosphate and additional potassium–magnesium sulfate were applied at planting in a double band 7 cm to the side and 5 cm below each seed piece to achieve total applications of 55 kg P ha^{-1}, 166 kg K ha^{-1}, 25 kg Mg ha^{-1}, and 45 kg S ha^{-1}.

The test cultivar was Russet Burbank, the most popular potato used for processing in the upper Midwest. Cut seed pieces (55–85 g) were hand-planted in open furrows the third week of April each year. Spacing was 90 cm between rows and about 25 cm between seed pieces in the row. Agrochemicals for the control of pests, diseases, and weeds were applied as needed with standard practice recommended for the crop in the area (Hutchison, 1996).

Soil moisture deficits of 25 mm or less during the vegetative and maturity stages and 14 mm or less during tuber bulking were maintained in the root zone (0–60 cm) with supplementary irrigation supplied according to the checkbook method (Wright and Bergsrud, 1991). Meteorological data were recorded hourly at a weather station within 1 km of the experimental plots.

To ensure greater leaching than occurred in the first two years of the study, an extra experiment (1999a) with the same N treatments was established in the same field in 1999 to receive irrigation based on early season rainfall events from a severe leaching year (Errebhi et al., 1998). Three times the amount of water applied in the standard-irrigation experiment was applied during the first three irrigation events in 1999. Subsequent irrigation was the same for the two irrigation regimes.

Two N sources, urea and a 70-d release formulation of PCU (Chisso Co., Tokyo, Japan[1]), were compared at 140 and 280 kg N ha^{-1}. The lower rate was the optimum obtained for PCU in a previous study (Zvomuya and Rosen, 2001), whereas the higher rate was based on prevailing fertilization practices of potato growers in central Minnesota (Bruening and Montgomery, 1995). Control plots that received no N were included in each replication. All PCU N was supplied in a single application at planting. Urea treatments received an initial 28 kg N ha^{-1} at planting, with the remaining N added in equal applications at emergence (28–30 days after planting, DAP) and hilling (37–45 DAP). Nitrogen applied at planting was banded together with the basal fertilizers during furrow opening. Application at emergence involved N addition in a double band 2.5 cm deep and 20 cm to each side of the plant row. At hilling, urea was surface-applied on either side of the hill and then incorporated into the hill within 6 h. An additional urea treatment (posthill) in 1998 and 1999 included 90 of the 280 kg N ha^{-1} as a 1:1 mixture of urea and ammonium nitrate applied in two additional splits 21 and 35 d after hilling. Posthill N was broadcast by hand on the crop canopy, followed immediately by irrigation to minimize urea N loss through volatilization. Many farmers in the region apply some of the N requirement of the potato crop as urea–ammonium nitrate (UAN) in irrigation water after hilling.

Treatments were replicated four times and arranged in a randomized complete block design. Each plot was 6 m in length in all years and either four (1997) or six rows wide (1998 and 1999). The change in plot width after 1997 was necessary to accommodate the extra row of ^{15}N-treated plants as described below.

The ^{15}N-labeled urea (5 atom %) and PCU (3.2 atom %) were applied in four replications in 1998 and three replications in 1999 to a 1.5-m section of an inner nonharvest row within the experimental plots. At planting, the preweighed labeled fertilizer was hand-applied in a double band at the same time nonlabeled fertilizer was applied, except that the posthill treatment received no labeled fertilizer.

Soil temperature at the depth of the fertilizer band was recorded every 30 min with two Optic StowAway loggers (Onset Computer Corp., Bourne, MA) installed in each of three replications. Soil moisture content at the same depth was measured with two CS615 water content reflectometers (Campbell Scientific, Logan, UT) connected to a CR10 datalogger that recorded measurements every 30 min.

Dissolution of Polyolefin-Coated Urea

In situ field incubation of PCU was undertaken in each experiment to characterize dissolution of the fertilizer. Eight to ten plastic mesh bags containing 3 g of fertilizer and 5 g of soil from the experimental field were buried within the fertilizer band at planting in nonharvest rows of appropriate plots in three replications. One mesh bag from each replication was retrieved every 2 to 3 wk for determination of total N. Dissolution of PCU as a function of time, accumulated mean soil temperature (AST), or growing degree days (GDD) was determined by regression. Accumulated mean soil temperature was calculated by summing mean daily soil temperatures recorded since the day of fertilizer application. Growing degree days were computed by subtracting 5°C from the mean daily soil temperatures, followed by summation of the adjusted mean daily soil temperatures. The rationale for this computation is that dissolution of PCU is limited if temperature falls below the threshold value of 5°C (Dr. Sadao Shoji, personal communication, 2001).

Estimation of Nitrate Nitrogen Leaching

Soil water was extracted with suction lysimeters with porous ceramic cups of 0.1 MPa air-entry pressure (Soilmoisture Equipment Corp., Santa Barbara, CA). The suction lysimeters were installed to a depth of 120 cm in the hill of a harvest row in 1997 and in the hill and furrow of a nonharvest row in 1998 and 1999. Samplers were installed in each plot (one lysimeter per plot in 1997 and two per plot in 1998 and 1999) in three replications within a week after planting. The samplers were installed vertically into slightly larger holes into which about 250 mL of silica flour had been added to improve hydraulic contact between the ceramic cup and the surrounding soil. Soil augured out during hole preparation was repacked into the hole after insertion of the samplers. The samplers were sealed with bentonite near the soil surface to minimize water

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[1] Names are necessary to report factually on available data; however, the USDA and the Univ. of Minnesota neither guarantee nor warrant the standard of the product, and the use of the name by the USDA and the Univ. of Minnesota implies no approval of the product to the exclusion of others that may be suitable.

flow along the shaft. Using a hand pump, a suction of 40 kPa was applied to collect samples from the soil water draining through the soil at the depth of installation. The 40-kPa vacuum was considered sufficient to maintain the suction in the cup above that of the surrounding soil until sample extraction. Solutions were extracted from the samplers with a hand pump at weekly or shorter intervals starting about 3 to 4 wk after planting. Samples were stored frozen until analysis. Nitrate and NH_4^+ in the soil solutions were determined by the diffusion–conductivity method described by Carlson et al. (1990).

After harvest of the potato crop, solution sampling tubing was buried beneath the Ap horizon to permit normal tillage operations and seeding of winter rye. The tubing was retrieved immediately after sowing and the disturbed areas around them resown.

Deep Percolation

Deep percolation under the potato crop was estimated on a daily basis at a depth of 120 cm with a simplified water balance equation (Waddell et al., 2000). The 120-cm depth was chosen to ensure that measurements were taken well below the root zone. The water balance between two consecutive days, *i* and *j*, was calculated as:

$$D = P + I - \Delta S - E \quad [1]$$

where D was the amount of daily drainage, P was precipitation, I was irrigation water applied, ΔS was change in soil water storage between two consecutive days, and E was evapotranspiration. The E values were calculated as a product of the crop coefficient (K_c) at a given crop development stage and potential evapotranspiration (E_o) estimated by a modified Penman equation (Wright and Bergsrud, 1991) with daily weather data recorded at the experimental site. Maximum water storage on any given day was equal to the soil water holding capacity (SWC) of the 120-cm soil profile. Beginning in early spring, the soil profile was set at SWC.

Nitrate leached in each sampling interval was calculated by multiplying NO_3–N concentration in the soil solution at successive sampling dates by the amount of drainage between the sampling dates. Although this method of calculation may not take into consideration daily fluctuations of NO_3–N concentration, possible errors were minimized by maintaining a continuous vacuum in the suction lysimeters and by sampling at short intervals (7 d or less). In 1998 and 1999, leaching losses from each plot were obtained by averaging the losses estimated under the hill (inrow) and under the furrow (between rows). Nitrate leaching for 1997 was calculated from inrow samplers only because no between-row sampling was done that year. Results from the three experiments in 1998 and 1999 indicated that at low to medium leaching levels, such as those obtained in the greater part of 1997, differences between inrow and between-row losses were small. Mean leaching losses from each treatment were summed over the growing season to give total N loss.

Harvesting and Plant Tissue Analysis

Before plot harvest, vines from the central two harvest rows and tubers and vines from the middle four plants in the ^{15}N microplots were harvested manually and weighed about 2 wk before tuber harvest. Potato tubers were mechanically harvested from the harvest rows during the third week in September each year. The tubers were graded into three size categories: <85 g, >85 g (marketable yield), and >170 g. Samples consisting of 25 potato tubers greater than 85 g were collected from each plot for determination of dry mass and measurement of specific gravity by the hydrometer method (Snack Food Association, 1995).

Tuber and vine samples from ^{15}N-labeled and unlabeled treatments were dried at 60°C and weighed for dry matter yield. Ground samples were analyzed for total N with a modified Kjeldahl method in which NO_3 is reduced by salicylic acid (Bremner, 1996). Ammonium in digests was determined conductimetrically (Carlson et al., 1990). Total N uptake was calculated as the product of total N concentration in plant tissue and dry matter yield. Atom % ^{15}N in plant samples from ^{15}N microplots and zero N plots was determined by spectrometric analysis with a Europa Scientific Integra isotope ratio mass spectrometer (PDZ Europa, Cheshire, UK) at the University of California–Davis Stable Isotope Facility.

Soil Sampling and Analysis

Six 2.5-cm-diameter soil cores were collected to a depth of 60 cm in the main plots immediately after harvesting. Cores from each plot were bulked and a subsample was taken for inorganic N determination. Air-dry soil samples were extracted with 2 *M* KCl and analyzed for residual NO_3–N (Carlson et al., 1990). Bulk densities measured from the study site (Gremy et al., 1993) were used to calculate the amount of NO_3–N in each plot.

Fertilizer Nitrogen Recovery Efficiency

The amount of N absorbed by tubers plus vines per kilogram of applied N (RE) was calculated based on ^{15}N (RE_{isot}) uptake by the crop and by the nonisotopic difference method (RE_{diff}). In the isotope method, RE was estimated from the ^{15}N enrichment measurements with the amount of fertilizer N applied (N_F) and the total N uptake by the crop (N_P), both expressed in kg N ha^{-1}:

$$RE_{isot}\ (\%) = (N_{dff}N_P/N_F) \times 100 \quad [2]$$

where the amount of N derived from the applied fertilizer, N_{dff}, is given by:

$$N_{dff} = (\text{atom \% }^{15}\text{N excess in plant tissue})/ (\text{atom \% }^{15}\text{N excess in fertilizer}) \quad [3]$$

using the ^{15}N abundance in the unfertilized potato plant as the background. The isotope method involves the assumption that biological interchange of labeled N with unlabeled N is negligible.

Calculation of recovery efficiency by the difference method was based on N uptake in control (N_0) and fertilized plots (N_{FP}), and the amount of fertilizer N applied (N_F):

$$RE_{diff} = [(N_{FP} - N_0)/N_F] \times 100 \quad [4]$$

An assumption of the difference method is that absorption of nonfertilizer N from the soil is the same for fertilized and control plants.

Statistical Analysis

Data from the study were analyzed with PROC GLM (SAS Institute, 1996). For the leaching data, analysis of variance was performed only on the total NO_3–N loss over the entire growing season. Data expressed as percentages were log-transformed before analysis to achieve normal distribution or homogeneity of variance. Data for each year were analyzed separately because treatments were expanded after 1997 and because preliminary analysis of variance on the pooled data indicated significant year by treatment interactions for the independent variables measured. Treatment means were compared using the Waller–Duncan test using a *k* ratio of 50, which corresponds to the 10% probability of making a Type I error (Steel and Torrie, 1997). For the dissolution study, slopes of the regression curves of cumulative nitrogen release (CNR) were compared using PROC GLM (SAS Institute, 1996).

RESULTS AND DISCUSSION

Weather and Percolation

Total rainfall for April through September in 1997 was 514 mm, and this was supplemented with 269 mm of irrigation. Drainage during the same period totaled 225 mm, 51% of which occurred in July. In 1998, total rainfall during the cropping season (462 mm) was below the 30-yr average (550 mm). Supplementary irrigation of 340 mm was applied during the season, bringing the total seasonal drainage volume to 195 mm. Total rainfall in 1999 was 26% above average. Irrigation amounts were 271 mm in the standard irrigation and 430 mm in the excessive irrigation experiment, resulting in drainage of 275 and 382 mm, respectively.

Dissolution of Polyolefin-Coated Urea

Cumulative N release was a quadratic function of time. Comparison of slopes of the regressions indicated that the quadratic functions were similar for the four experiments ($p > 0.1$). Dissolution of PCU was therefore described by a single quadratic equation with an x intercept of 14 d after fertilization (Fig. 1). The regression suggests that 60% of applied PCU N, or 84 and 168 kg N ha^{-1} for the 140 and 280 kg N ha^{-1} rates, respectively, was released by harvest time (about 150 d after application). There was no measurable N release during the first 2 wk after fertilizer application.

Because of the thermoplastic nature of its polyolefin coating, PCU may require a specific number of growing degree days (GDD) to release a given fraction of N regardless of the number of days after application to the soil. Polynomial orthogonal contrasts were therefore tested on the data to determine whether GDD could be used to predict N release from PCU. A quadratic equation relating PCU dissolution to GDD adequately described pooled data for the four experiments (Fig. 2). The equation indicates that 60% of PCU N had been released by about 2000 degree days, which corresponds to harvest time.

Our data also indicate that CNR and accumulated average soil temperature (AST) were related by the equation: $CNR = -1.23 + 0.032 \times AST - 3.55 \times 10^{-6} AST^2$ ($r = 0.96, p < 0.001$). According to this equation, 60% of PCU N was released at an AST of about 2750. This is a much lower dissolution than that reported for the same fertilizer in a study by Gandeza et al. (1991). According to these authors, 80% of total PCU N should have been released by harvest in our study. The difference between the two studies suggests that although PCU dissolution is primarily determined by soil temperature, other environmental factors may also be important in determining the rate of dissolution. Polyolefin-coated urea dissolution may therefore vary from one location to another. It is therefore necessary that an appropriate formulation is prescribed for each location regardless of similarities in temperature variations. Since the growing season for Russet Burbank potatoes in central Minnesota ranges up to 150 d and the 70-d PCU releases only 60% of its total N during this period, a quicker-release PCU formulation may be needed to maximize N availability to the crop and minimize potentially leachable residual N in the soil.

Nitrate Leaching

In all experiments, NO_3 leaching was highest following major rainfall and irrigation episodes (Fig. 3). At

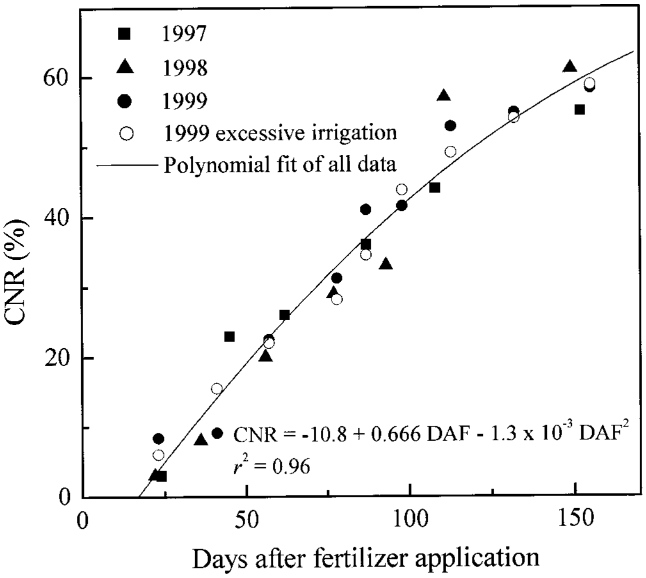

Fig. 1. Cumulative nitrogen release (CNR), expressed as a percentage of total N applied, from polyolefin-coated urea (PCU) incubated at the depth of the fertilizer band in the potato hill as a function of number of days after fertilizer application (DAF).

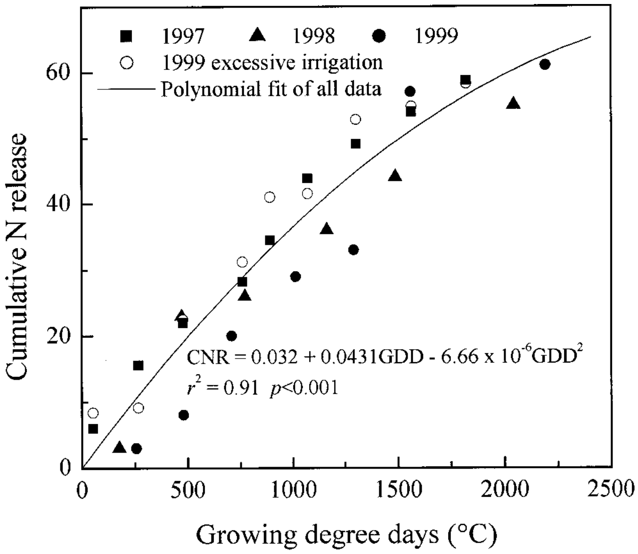

Fig. 2. Cumulative nitrogen release (CNR), expressed as a percentage of total N applied, from polyolefin-coated urea (PCU) incubated at the depth of the fertilizer band in the potato hill as a function of cumulative growing degree days (GDD; base of 5°C) after fertilizer application.

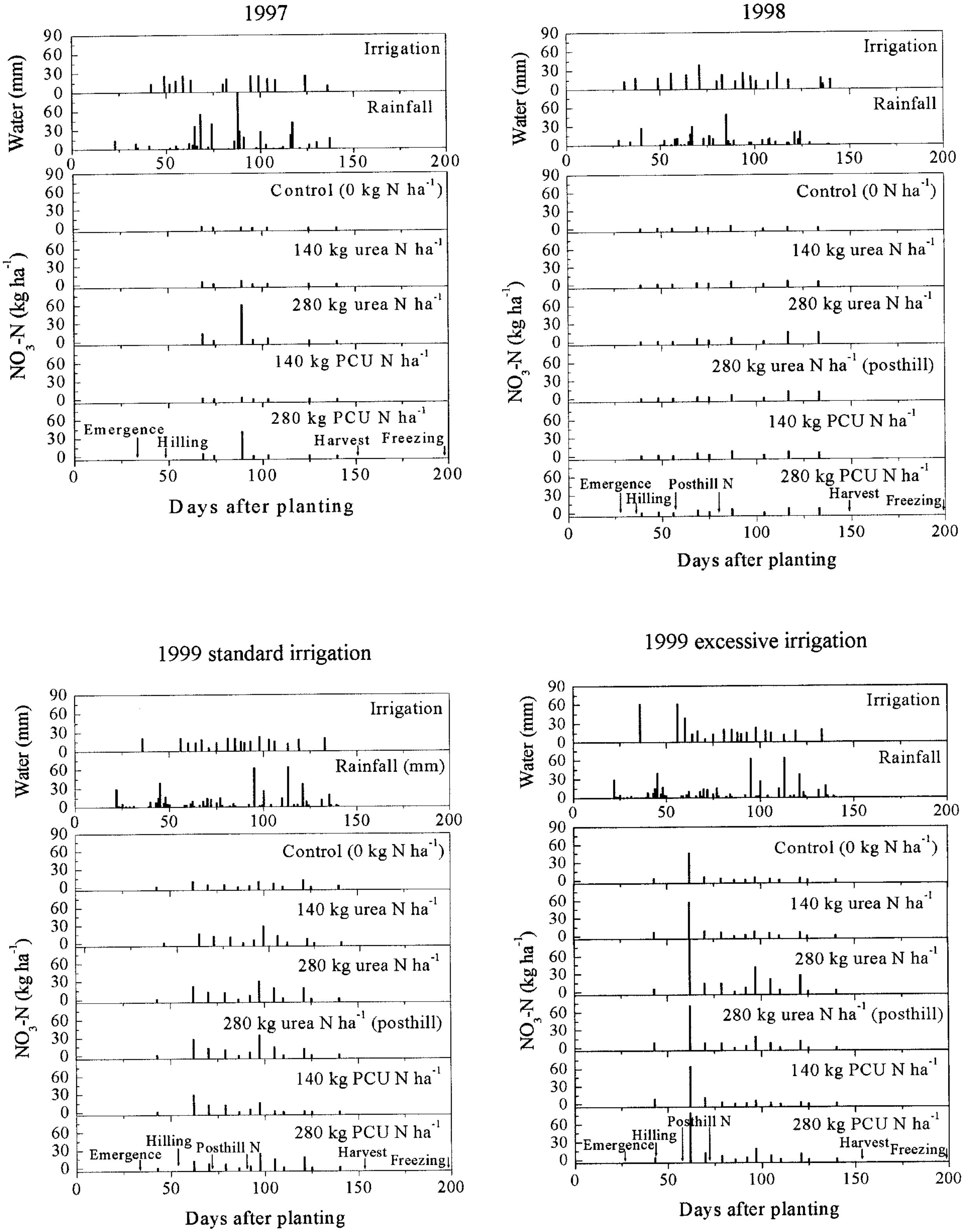

Fig. 3. Rainfall and irrigation distribution and daily nitrate leaching during the potato growing seasons at Becker, Minn., in 1997, 1998, and in the standard and excessive irrigation experiments in 1999.

least 75% of the leaching losses from all treatments in 1997 occurred during the first three weeks in July (67–89 DAP). In 1998, only two leaching episodes with drainage volumes above 20 mm were observed at 66 (24 mm) and 84 DAP (35 mm). In the standard irrigation experiment in 1999, nearly one half of the total seasonal losses for each treatment occurred during the two sampling intervals ending 62 and 97 DAP. More than 40% of total

Table 1. Effect of fertilizer treatment on cumulative NO_3 leaching during the potato growing season at Becker, MN.

N rate	N source†	Experiment			
		1997	1998	1999	1999a‡
kg ha^{-1}		kg NO_3–N ha^{-1}			
0		4e§	15d	52c	68d
140	urea	13c	23c	66b	98c
	PCU¶	7d	27bc	62bc	94c
280	urea	87a	47a	84a	228a
	PCU	45b	28bc	56bc	143b
	posthill#	–	36ba	90a	135b

† 28 kg ha^{-1} of urea applied at planting, and the remainder split equally between emergence and hilling. All polyolefin-coated urea (PCU) was added in a single application at planting.

‡ Excessive irrigation experiment.

§ Means within columns followed by the same letter are not significantly different, based on the Waller–Duncan Bayesian *t* test with a *k* ratio of 50.

¶ Split-applied at planting (28 kg N ha^{-1} as urea), emergence (81 kg N ha^{-1} as urea), and hilling (81 kg N ha^{-1} as urea), with the remaining 90 kg N ha^{-1} applied in equal splits at 3 and 5 wk after hilling as a 1:1 mixture of urea- and ammonium nitrate-N.

seasonal losses in 1999 under excessive irrigation occurred between 43 and 62 DAP.

Nitrogen fertilizer additions generally increased NO_3 leaching compared with the control. Timing of NO_3 losses was closely related to heavy rainfall events (or excessive irrigation), regardless of potato growth stage. For all treatments, total NO_3 loss by leaching was highest in 1999 under excessive irrigation (Table 1). In all years, NO_3 leaching was 40% lower with PCU at 280 kg N ha^{-1} than the same rate of N as urea. Seasonal leaching at the high rate was lowest in 1998, reflecting the relatively low total drainage volume (195 mm) during that season. At the low N rate, NO_3 leaching was similar for the two N sources, except in 1997 when leaching from PCU was 45% lower than urea. Under excess irrigation in 1999, the posthill treatment reduced leaching compared with three splits of urea and resulted in similar leaching as PCU. This indicates that under conditions of excessive leaching, increased frequency of application of soluble urea N can be nearly as beneficial as PCU in decreasing N leaching. Under standard irrigation in 1999, however, NO_3–N leaching with the posthill treatment did not differ from the three-split urea treatment and was higher than the PCU treatment. The higher cumulative NO_3 leaching that occurred in the control plots in 1999 compared with 1997 and 1998 was probably due to N from mineralization of the previous soybean crop.

With the exception of the 1998 experiment when leaching at the high N rate was small, cumulative seasonal leaching values reported in this study agree with those from previous studies (Hill, 1986; Errebhi et al., 1998), which ranged from 78 to 257 kg N ha^{-1} for soluble N fertilizers applied to potatoes.

Water sampling continued until freezing in November (about 200 DAP) each year and resumed the following spring under the succeeding rye crop. No measurable leaching occurred between harvest and freezing in any experiment due to dry conditions. Similarly, in the absence of irrigation and leaching rainfall, no significant percolation occurred in the subsequent year when the plots were cropped with rye. However, NO_3–N concentrations, averaged across experiments and N rates, in water samples collected until harvest of the rye crop in mid-July each year were highest in plots previously fertilized with PCU (mean 6.9 mg L^{-1}) and averaged 3.2 mg L^{-1} for urea and the control. Although all concentrations were below the 10 mg L^{-1} limit, it is apparent that this limit could be exceeded if the plots were to remain fallow the year following PCU application. These results indicate the importance of a subsequent crop in lowering the risk of NO_3 leaching in potato fields that have received PCU N, or of selecting PCU that has a faster dissolution rate in this environment.

Dry Matter Yield

Tuber, vine, and total dry matter (DM) yields increased with N application in all experiments except 1998, when vine DM did not respond to low N application regardless of source (Table 2). Urea and PCU supported similar DM yields, except in 1997 when vine DM at 140 kg N ha^{-1} was higher with urea, whereas PCU gave higher total DM yield at the 280 kg ha^{-1} rate. Total DM with five split applications was less than total DM with PCU or urea in three split applications in 1998 and 1999 under standard irrigation.

Tuber Specific Gravity

Russet Burbank potatoes in the upper Midwest are grown primarily for processing; therefore, tuber specific gravity is of primary importance since it determines the weight of processed product that can be recovered from a given weight of potato tubers (Kleinkopf et al., 1987). With the exception of the control and low N treatments in 1998, all specific gravity values were greater than 1.080, indicating high tuber quality suitable for processing and other uses (Table 2). At equivalent N rate, specific gravity was similar for urea and PCU in all years. Doubling the rate of N application from 140 to 280 kg ha^{-1} resulted in significantly higher specific gravity for urea in 1998 and for PCU in the excessive irrigation experiment in 1999. Martin et al. (1993) reported a similar rate effect for the cultivar 'Atlantic' in Florida. However, this finding contradicts other studies where reductions in specific gravity were reported at higher rates of applied N (e.g., Ojala et al., 1990). Westermann and Kleinkopf (1985) demonstrated that treatments, such as higher N rate, that increase tuber yields often reduce specific gravity.

Tuber Yield

All N treatments significantly improved total and marketable tuber yield compared with the zero N control in all experiments, with the exception of the 140 kg N ha^{-1} urea treatment in 1998, which produced similar total yield as the control (Table 2). Total and marketable yields were higher with PCU than with three applications of urea at both the 140 and 280 kg N ha^{-1} rates in 1997 and at 280 kg N ha^{-1} under excessive irrigation in 1999, but the difference between the two sources at equivalent rates was not significant in 1998 and under standard irrigation in 1999. There was no benefit in total

Table 2. Effect of source and rate of N application on yield and dry biomass of Russet Burbank potato tubers at Becker, MN.

Year	N rate	N source	Fresh tuber yield			Specific gravity	Dry matter		
			Total	Marketable†	>170 g‡		Tuber	Vine	Total
			Mg ha^{-1}	Mg ha^{-1}	%		Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}
1997	0		36.6c§	30.5d	51c	1.080b	7.7b	0.6d	8.3c
	140	urea	45.9b	41.8c	68b	1.087a	10.6a	2.9a	13.5a
		PCU¶	51.6a	47.4ab	76a	1.085a	11.2a	1.2cd	12.4ab
	280	urea	45.9b	43.5bc	75a	1.088a	10.5a	1.4bc	12.0b
		PCU	51.7a	48.8a	79a	1.086a	11.7a	2.0b	13.7a
1998	0		50.2c	29.6c	19d	1.077c	9.1d	0.4c	9.5c
	140	urea	57.0bc	41.6b	43bc	1.078c	10.8c	0.6c	11.4b
		PCU	59.3ab	43.5b	38c	1.080bc	11.4abc	0.9bc	12.2b
	280	urea	63.2ab	49.8a	51ab	1.084a	12.5a	1.3ab	13.8a
		PCU	64.2a	47.6a	55a	1.083ab	12.0ab	1.4a	13.4a
		posthill	60.1ab	43.8b	58a	1.083ab	10.9bc	1.4a	12.3b
1999	0		63.7b	56.9b	53c	1.085a	12.9b	1.3c	14.1d
	140	urea	74.1a	68.7a	73b	1.085a	15.2a	2.5b	17.6c
		PCU	74.6a	69.1a	72b	1.086a	15.1a	2.9b	18.0bc
	280	urea	79.0a	73.5a	76a	1.085a	16.1a	3.6a	19.7a
		PCU	77.2a	72.7a	78a	1.081a	15.6a	3.7a	19.3ab
		posthill	74.0a	68.2a	76a	1.086a	14.5ab	3.1ab	17.6c
1999a#	0		55.3d	46.9d	40d	1.082b	11.4c	1.3d	12.7c
	140	urea	73.2bc	67.3bc	64c	1.085ab	14.8b	2.7c	17.5b
		PCU	76.3b	70.5b	68bc	1.082b	16.1ab	2.4c	18.5ab
	280	urea	71.1bc	65.2bc	70b	1.085ab	15.5ab	2.8bc	18.3ab
		PCU	82.0a	77.5a	77a	1.086a	17.0a	3.7ab	20.6a
		posthill	69.6c	63.2c	70b	1.086a	14.8b	3.9a	18.8ab

† Marketable yield = total yield − undersize (<85 g) tuber yield.
‡ Expressed as percentage of marketable yield (i.e., yield of tubers > 85 g).
§ Means followed by the same letter in columns within each year are not significantly different according to the Waller–Duncan Bayesian *t* test (*k* ratio = 50).
¶ Polyolefin-coated urea.
# Excessive irrigation experiment.

and marketable yield from applying urea N in five compared with three splits in any of the experiments, but PCU at 280 kg N ha^{-1} resulted in higher marketable yield in 1998 and higher total and marketable yields under excessive irrigation in 1999 than five applications of urea. Doubling the N rate from 140 to 280 kg ha^{-1} resulted in higher marketable yield for both sources in 1998 and higher total and marketable yields for PCU under excessive irrigation in 1999. The percentage of marketable tubers greater than 170 g, which are desirable for processing, was similar or higher for PCU than urea. Doubling the N rate from 140 to 280 kg ha^{-1} resulted in a similar or greater percentage of marketable tubers in this category.

Differences in yield between the two N sources in 1997 and under excessive irrigation in 1999 could be due to high and, in the case of the latter experiment, earlier leaching, which resulted in greater NO_3 loss compared with 1998 and 1999 under standard irrigation, as discussed below. Westermann and Kleinkopf (1985) noted that decreased N uptake resulting from depleted soil NO_3–N can reduce tuber bulking rates, size, and yields. Because PCU releases N slowly, N loss through leaching is minimized, resulting in higher yields and larger tubers compared with urea. It has also been reported that the benefits of CRFs relative to soluble fertilizers in potato production are associated with the continued supply of N during tuber bulking and earlier tuber initiation (Cox and Addiscott, 1976).

The present results corroborate earlier findings by Zvomuya and Rosen (2001). These authors obtained higher yields and larger tubers with a 1:1 blend of 50- and 70-d PCU formulations than three applications of urea during leaching seasons. In a majority of studies, traditional CRFs have resulted in lower potato yields than soluble fertilizers (Lorenz et al., 1972; Cox and Addiscott, 1976; Waddell et al., 1999). Poor performance of the CRFs in these studies was mostly due to unpredictable release of N, which did not match crop demand.

The absence of source or rate effects on total and marketable yields in the standard irrigation experiment in 1999 may have been due in part to the effect of the previous soybean crop. Potato yield response to N fertilization is often limited following a legume crop (Bélanger et al., 2000) due to release of N through mineralization during the growing season. Tuber size, however, increased with increased N even when total and marketable yields were not affected in our experiment.

Nitrogen Recovery

Fertilizer N generally increased tuber, vine, and total N uptake compared with the control in all experiments, with a few exceptions (Table 3). Total and tuber N uptake increased in all experiments as PCU N rate doubled from 140 to 280 kg ha^{-1}. Except in 1998, N uptake from PCU by the vines responded similarly. In contrast, doubling the N rate as urea increased total, tuber, and vine N uptake only in 1998 and under standard irrigation in 1999. At 280 kg N ha^{-1}, N recovery in the tubers, vines, and tubers plus vines (total) was 45% higher with PCU than urea application in 1997 and 23% higher under excessive irrigation in 1999. In 1998 and 1999 (standard irrigation), recoveries were similar for PCU and urea at the high N rate. The posthill treatment resulted in lower total N recovery than the equivalent rate of PCU N in

Table 3. Effect of N treatment on uptake and recovery of fertilizer N applied to Russet Burbank potato as measured by the difference and isotope methods.

Year	N rate	N source	N uptake Tuber	N uptake Vine	N uptake Total	RE_{diff}†	RE_{isot}‡
	kg ha^{-1}		kg N ha^{-1}	kg N ha^{-1}	kg N ha^{-1}	%	%
1997	0		69d§	4c	73c	–	–
	140	urea	113c	21a	133b	43a	–
		PCU¶	140b	10c	150b	55a	–
	280	urea	129bc	13bc	142b	25b	–
		PCU	181a	26a	206a	48a	–
1998	0		80e	8b	88c	–	–
	140	urea	121d	12b	133b	32a	37b
		PCU	128cd	14ab	143b	39a	43a
	280	urea	160ab	27a	187a	35a	35b
		PCU	168a	27a	195a	38a	40ab
		posthill	14bc	27a	174a	31a	–
1999	0		109c	11c	120d	–	–
	140	urea	188b	29b	218c	56ab	62b
		PCU	190b	33b	223c	60a	73a
	280	urea	236a	56a	292a	55ab	53b
		PCU	227a	67a	294a	55ab	58b
		posthill	206b	52a	259b	43b	–
1999a#	0		99c	10c	109c	–	–
	140	urea	175b	29b	207b	58a	49bc
		PCU	179b	38b	217b	64a	63a
	280	urea	188b	37b	224b	35c	43c
		PCU	228a	49a	277a	54ab	59ab
		posthill	174b	53a	226b	36bc	–

† $RE_{diff} = 100 \times$ (N uptake in fertilized plots − N uptake in control plots)/N rate.

‡ $RE_{isot} = 100 \times$ (fraction of N derived from fertilizer * total N uptake by the crop)/N rate.

§ Means within columns within a year followed by the same letter are not significantly different, based on the Waller–Duncan Bayesian *t* test with a *k* ratio of 50.

¶ Polyolefin-coated urea.

Excessive irrigation experiment.

1999 under excessive leaching and than PCU and urea under standard irrigation in 1999. In 1998, total N uptake at each N rate was similar among N sources and managements, reflecting the lower leaching during that season. At the 140 kg N ha^{-1} rate, N uptake by tubers, vines, and the whole plant was similar for the two sources, except in 1997 when tuber N uptake was higher with PCU and vine N uptake was higher with urea.

Nitrogen uptake in 1997 and 1998 was within the range reported in previous studies (Errebhi et al., 1998; Meyer and Marcum, 1998). In 1999, N recovery for all treatments in the present study tended to be higher than obtained in the studies by Errebhi et al. (1998) and Meyer and Marcum (1998). High mineralized N from the previous soybean crop in 1999 and higher yield potential may have resulted in large amounts of N being available for uptake by the crop during that year. Lower N recovery in 1997 and 1998 may be due in part to immobilization of applied fertilizer N into soil organic matter. Bowman et al. (1998) cited immobilization of N as the most likely reason why a portion of the ^{15}N applied to creeping bentgrass (*Agrostis stolonifera* L.) was not accounted for in the N budget. In the UK, Webster et al. (1999) suggested that most of the N unaccounted for in their study (up to 150 kg ha^{-1}) was immobilized. Differences in the extent of immobilization may explain the discrepancies between N recovered following winter rye in 1997 and 1998 and that following soybean under standard and excessive irrigation in 1999. Immobilization is expected to be much higher following the cereal, which has a higher C to N ratio. This possibility emphasizes the need for further experiments to investigate the extent of immobilization when potatoes are grown in rotation with winter rye compared with soybean.

Nitrogen RE for PCU estimated by the difference method was 93% higher in 1997 and 54% higher under excessive irrigation in 1999 than urea at 280 kg N ha^{-1} (Table 3). The posthill treatment resulted in similar N RE estimates as PCU and three urea applications in 1998 and in both experiments in 1999. Recovery efficiencies estimated using the isotope method (RE_{isot}) were higher for PCU than urea at the 140 kg N ha^{-1} rate in all three experiments and at the 280 kg N ha^{-1} rate under excessive irrigation in 1999. Results for the higher N rate follow a pattern similar to those obtained for the percentage of total plant N derived from fertilizer (total N_{dff}) (Table 4). However, total N_{dff} was significantly higher with PCU than urea only in 1999 under excessive irrigation at the high N rate, with PCU out-performing urea by 13%. At 140 kg N ha^{-1}, total N_{dff} was similar for urea and PCU N in all three experiments. The percentage of tuber N derived from fertilizer (tuber N_{dff}) was higher with PCU than urea in 1999 at both rates in the excessive irrigation experiment and at the higher rate under standard irrigation. Vine N_{dff} was higher with PCU in 1999 under excessive irrigation. Because the posthill treatment was not labeled, comparisons with other treatments cannot be made using the isotope method.

Recovery efficiency tended to decrease at the higher N rate, although, in the isotope method, this was significant only for PCU in the standard irrigation experiment in 1999. With the difference method, the difference between N rates was significant only for urea in 1997 and 1998, when NO_3 leaching losses were relatively low.

Table 4. Percentage of N in Russet Burbank tuber, vine, and tuber plus vine (total) that was derived from applied fertilizer, as determined by ^{15}N enrichment.

			N derived from applied fertilizer		
Year	N rate	N source	Tuber	Vine	Total
	kg ha^{-1}		%		
1998	140	urea	39b†	30b	38b
		PCU‡	44b	31b	42b
	280	urea	52a	47a	52a
		PCU	57a	48a	55a
1999	140	urea	40c	31b	39b
		PCU	44c	36ab	43b
	280	urea	50b	45a	51a
		PCU	57a	44a	55a
1999a§	140	urea	43d	33c	42c
		PCU	45c	36c	44c
	280	urea	57b	44b	55b
		PCU	65a	50a	62a

† Means within columns followed by the same letter are not significantly different, based on the Waller–Duncan Bayesian *t* test with a *k* ratio of 50.
‡ Polyolefin-coated urea.
§ Excessive irrigation experiment.

The low recovery of urea N, particularly at the high rate under excessive irrigation in 1999, reflects the large leaching losses of N that occurred early in the season. Under the low leaching conditions in 1998, recovery of applied N was similar for PCU and soluble N treatments. Using the difference method, Errebhi et al. (1998) reported recoveries averaging 33% during a leaching season and 56% during a nonleaching year for Russet Burbank potatoes fertilized with 270 kg soluble N ha^{-1} on a similar soil. In other studies, recoveries of 50 to 60% have been reported for Russet Burbank potatoes fertilized with soluble N fertilizers (Joern and Vitosh, 1995). Based on the dissolution rate of the PCU and at the recommended rate of 280 kg N ha^{-1}, the RE_{diff} values obtained in this study translate to recoveries of 80, 64, and 91% of released N for 1997, 1998, and 1999, respectively. Corresponding recoveries of released N using the RE_{isot} method were 67% and 98% for 1998 and 1999, respectively.

The isotope method tended to be more precise, that is, more differences were found using N RE_{isot} than N RE_{diff} (Table 3). A comparison of the difference and ^{15}N methods performed on combined data for the 1998 and 1999 experiments showed that RE values estimated by the isotope method (mean = 51%) were significantly greater ($p \leq 0.1$) than those obtained using the difference method (mean = 47%). There was good correlation between the two methods ($r = 0.77$; $p \leq 0.001$). Interactions involving estimation method were not significant ($p > 0.1$), indicating that the relationship between the methods did not change with N rate or experiment. The higher RE values obtained with the isotope method in the present study cannot be easily explained. However, these results suggest the absence of added N interactions, which are used to explain the higher RE values often reported for the difference method (Bronson et al., 2000).

Residual Soil Nitrogen

Total mineral (NH_4^+ NO_3) N remaining in the top-60-cm soil depth at harvest was significantly higher ($p <$ 0.1) with PCU than urea or the posthill treatment at both N rates in the standard irrigation experiment in 1999 and at the 140 kg N ha^{-1} rate in the excessive irrigation experiment the same year (Table 5). Similar results were reported in corn by Cartagena et al. (1995), who obtained higher residual mineral N from plots treated with CRFs compared with soluble N fertilizers. These results suggest the need for a cover crop following potato harvest if PCU is used.

Table 5. Effect of N treatment on residual soil mineral N content in the 0- to 60-cm depth at harvest.

N rate	N source	1997	1998	1999	1999a†
kg ha^{-1}		kg N ha^{-1}			
0		30a‡	36b	22d	20c
140	urea	37a	52a	27cd	25bc
	PCU§	38a	52a	58ab	40a
280	urea	35a	50a	31c	33ab
	PCU	40a	58a	72a	37a
	posthill	–	56a	47b	34a

† Excessive irrigation experiment.
‡ Means within columns followed by the same letter are not significantly different, based on the Waller–Duncan Bayesian *t* test with a *k* ratio of 50.
§ Polyolefin-coated urea.

CONCLUSIONS

Results from this study demonstrate that PCU can produce similar or higher potato yields than urea at equivalent N rates. At the N rate recommended for Russet Burbank potatoes in central Minnesota (280 kg N ha^{-1}), a single application of 70-d PCU improved recovery of applied N and reduced NO_3 leaching, particularly under excessive leaching conditions, compared with three applications of urea. Applying urea in five instead of three applications may reduce leaching losses to levels similar to those for PCU in some seasons, but recovery of fertilizer N may still be lower than for PCU under severe leaching. At the recommended rate of 280 kg N ha^{-1}, fertilizer N RE was, on average, higher with PCU (mean 50%) than urea (mean 43%). Residual N tended to be higher with PCU due to its slow release rate in this environment. Under conditions of this study, a quicker release product may be needed to minimize residual N in the soil.

Results from this study suggest that PCU may be a better option than urea in areas where N leaching from potato fields is a serious problem. However, the additional cost associated with the use of PCU to reduce leaching cannot currently be justified (Zvomuya and Rosen, 2001) without economic values being placed on the quality of the ground water resource.

ACKNOWLEDGMENTS

This research was supported by a grant from the Minnesota Water Resources Research Institute. Additional support was provided by Chisso Co., Japan.

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