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Polymer Coated Urea in 'Russet Burbank' Potato: Yield and Tuber Quality

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Abstract

Nitrogen (N) fertilizer applied as polymer coated urea (PCU) may have the potential to improve potato (*Solanum tuberosum* L.) production. The objectives of this study were to determine the effects of PCU on potato yield and quality. 'Russet Burbank' potato was grown at three Idaho, USA locations. Five rates of N (0, 33, 67, 100, and 133% of the recommended rate) were applied in all combinations of: PCU applied at emergence, urea applied at emergence, or urea split-applied. The PCU-fertilized treatments produced 11%, 11%, and 10% higher US No. 1, marketable and total tuber yields, respectively, than urea-split applied. PCU trended toward increased tuber size. At equivalent rates, PCU was more efficient than urea N in providing N to potato. These results confirm findings from other researchers that a single application of PCU fertilizer, just prior to emergence, can efficiently meet seasonal N requirements for Russet Burbank potato.

Resumen

El fertilizante nitrogenado (N) aplicado como urea recubierta de polímero (PCU) puede tener el potencial de mejorar la producción de papa (*Solanum tuberosum* L.). Los objetivos de este estudio fueron determinar los efectos de la UCP en el rendimiento y la calidad de la papa. La papa 'Russet Burbank' se cultivó en tres localidades de Idaho, EUA. Se aplicaron cinco tasas de N (0, 33, 67, 100 y 133% de la dosis recomendada) en todas las combinaciones de: UCP aplicada en emergencia, urea aplicada en emergencia o urea aplicada dividida. Los tratamientos fertilizados con PCU produjeron rendimientos de tubérculos 11%, 11% y 10% más altos en la categoría US No. 1, comercializables y totales, respectivamente, que los aplicados por división de urea. La UCP tendió hacia un aumento del tamaño del tubérculo. A tasas equivalentes, la UCP fue más eficiente que la urea N para proporcionar N a la papa. Estos resultados confirman los hallazgos de otros investigadores de que una sola aplicación de fertilizante PCU, justo antes de la emergencia, puede cumplir eficientemente con los requisitos estacionales de N para la papa Russet Burbank.

Keywords Nitrogen · Urea · Polymer Coated Urea · Potato · *Solanum tuberosum*

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Abbreviations

EEF	Enhanced Efficiency Fertilizer
ESN	Environmentally Smart Nitrogen
GSP	Grower's Standard Practice
NUE	Nitrogen Use Efficiency
NDVI	Normalized Difference Vegetative Index
PCU	Polymer Coated Urea

Introduction

Providing the food, fuel, and fiber for the nearly eight billion people on the planet is of paramount importance (Barker and Pilbeam 2015; Hillel 1991). Among the crops grown for this purpose, potato (*Solanum tuberosum* L.) is surpassed in global value by only three grain crops and ranks first among vegetable crops in both acreage and value (Hopkins and Hansen 2019).

Potato and other crop production remove essential nutrients from the system as the harvested tissue (e.g., grains, tubers, forages, etc.) is transported away from the field. Without proper nutrient management, agricultural soils eventually become infertile (Barker and Pilbeam 2015; Hillel 1991; Hopkins 2020). Addition of nutrients to the soil by fertilization is essential for maintaining adequate nutrient uptake needed for plant growth, especially in high yield systems (Hopkins and Hansen 2019).

Potato requires more fertilizer than most crops, primarily due to relatively high nutrient demand and a somewhat shallow, inefficient rooting system (Fixen and Bruulsema 2014; Hopkins et al. 2014, 2020; Hopkins and Hansen 2019; Munoz et al. 2005; Pack et al. 2006; Wilson et al. 2009) As a result, recommended rates of major nutrients needed for economically optimum yields (Hopkins et al. 2007) are substantially higher for potato compared to many other crops (Fixen and Bruulsema 2014; Hopkins and Hansen 2019; Hopkins et al. 2020; Joern and Vitosh 1995a; Prunty and Greenland 1997; Zvomuya et al. 2003; Munoz et al. 2005). This is especially true for nitrogen (N) (Geary et al. 2015; Hopkins et al. 2020; Zebarth and Rosen 2007).

Arguably, N is the nutrient with greatest impact on plant growth and is the most commonly deficient plant nutrient in managed agricultural systems (Hopkins 2020; Pilbeam 2015; Ransom et al. 2021; Kitchen et al. 2022). Thus, N is the most applied element, with approximately half of all fertilizer sold being an N source (Hopkins 2020). This essential macronutrient is involved in nearly every plant part and process as a component in amino acids, alkaloids, and chlorophyll. Plants require N at adequate levels for optimal growth (Geary et al. 2015; Kitchen et al. 2022; Pilbeam 2015).

Most traditional potato varieties, such as 'Russet Burbank', are relatively sensitive to both N deficiency and excess (Biemond and Vos 1992; Errebhi et al. 1999; Geary et al. 2015; Hopkins et al. 2020; Miller and Hopkins 2007; Zebarth and Rosen 2007). Excess N often results in excessive vine growth at the expense of tuber yield, increased disease, and reduced tuber quality (size and shape). Deficient N commonly results in poor plant growth and yields/crop quality.

Ecosystems are also sensitive to excessive N (Buck et al. 2016; Hopkins 2020; Kitchen et al. 2022). As nitrate (NO_3^-) is poorly retained by soils, it can easily escape the root zone by leaching. Excess N can result in a buildup of NO_3^- in groundwater, which is a livestock and human drinking water health concern (Bero et al. 2014). Additionally, transport of N to surface water can lead to algal blooms, which may result in eutrophication and/or direct toxicity to aquatic and other organisms (Jarvie et al. 2020). Improperly managed N (i.e., incorrect rates, timing, incorporation, etc.) also adds to an increase in atmospheric pollution through nitrous oxide (N_2O) emission and ammonia (NH_3) volatilization (Gao et al. 2017; Hopkins 2020; Hyatt et al. 2010; LeMonte et al. 2016, 2018; Ruser et al. 1998; Shoji and Kanno 1994; Venterea et al. 2011; Wang and Alva 1996; Zebarth et al. 2012). The N loss to the environment can be especially high when dealing with potato due to high fertilizer and irrigation rates, as well as an inefficient root system (Hopkins et al. 2020).

Best Management Practices have been developed for optimal crop production and economic returns (Hopkins et al. 2007, 2020; Zebarth and Rosen 2007). Optimizing the efficiency of fertilizers can reduce their impact on the environment while maintaining crop yield and economic profitability. Because potato needs a steady supply of N throughout the growing season, it is recommended that N availability be synchronized with plant demand to maximize N Use Efficiency (NUE) and yield and tuber quality (Errebhi et al. 1998; Gayler et al. 2002; Hopkins et al. 2008, 2020; Joern and Vitosh 1995b; Munoz et al. 2005; Prunty and Greenland 1997; Ruser et al. 1998; Singh and Sekhon 1976; Saffigna et al. 1977; Waddell et al. 1999, 2000; Westermann and Kleinkopf 1985; Westermann et al. 1988). Growers will often apply 25–40% of the predicted total N requirement for the crop before or at plant emergence. This N can be applied in one application or a combination of pre-plant, at-planting, and side dress applications once plants emerge. The rest of the required N is applied in increments throughout the remainder of the growing season. These applications are typically made as injections into the irrigation system (fertigation) or as broadcast applications via air or ground-based fertilizer spreaders. The total N rate is typically estimated based on preplant soil tests and fertilizer recommendations derived from N rate research, and in-season rates are based on weekly samples of petiole tissue and, sometimes, soil samples.

Although the practice of "spoon feeding" the N in this manner can help increase tuber yield and quality, it is labor and equipment intensive and, as a result, more costly. And there are some irrigation systems that cannot be used to inject fertilizer because of the lack of the proper equipment (i.e., backflow valves). In many potato producing regions, there is ample precipitation and growers do not rely a great deal or at all on irrigation, making fertigation for in-season applications a poor or non-existent option. These constraints limit growers to applying the required N in one pre-emergent application or in combination with costly aerial/ground-based broadcast applications. However, aerial application is not permissible or safe in some cases and ground application results in field damage as a fertilizer spreader drives through a fully developed canopy. In all cases, the cost in both time and money of spoon-feeding N applications is significant. In addition, liquid forms of N that are injected into the irrigation system are typically more costly than the dry forms that are commonly applied pre-emergence.

Urea [$CO(NH_2)_2$] is the most common fertilizer N source (Hopkins 2020), especially for dry broadcast applications pre-plant or shortly after. Urea is considered a "quick release" fertilizer as it dissolves rapidly upon hydration. In contrast, most crop residues and animal waste sources are, in effect, "slow release" fertilizers with the N becoming available slowly as decomposition occurs (Hopkins and Hirnyck 2007). There are also manufactured fertilizers that are slow or even control release that also meter out the N over time (Hopkins 2020). These slow/control release fertilizers only make up a small fraction of current global production (Hopkins 2020).

Controlled or slow-release N sources are one class of Enhanced Efficiency Fertilizers (EEF) that release N into the soil gradually over an extended time, rather than as a rapid flush of a large amount of soluble N into the soil solution (Hopkins 2020). This potentially provides an improvement in synchronizing the N release to the plant's needs throughout the growing season. Application of these fertilizers may even eliminate or reduce labor intensive and costly in-season N applications, as well as increase NUE and improve environmental quality (Alva 1992; Hopkins 2020; Hutchinson et al. 2003a; Mikkelsen et al. 1994; Munoz et al. 2005; Pack et al. 2006; Shoji and Kanno 1994; Wang and Alva 1996; Shoji et al. 2001; Zvomuya et al. 2003).

Polymer Coated Urea (PCU) is a controlled release product that is comprised of granulated N fertilizer with a thin polymer coating surrounding each urea granule (Hopkins 2020; Trenkel 1997; Vejan et al. 2021). The N is released at a controlled rate gradually into the soil solution (Ransom et al. 2020; Trenkel 1997), with the rate of release proportional to soil temperature and coating thickness. By releasing N over time, the N is more likely taken up by plant roots rather than lost through volatilization or leaching. Use of PCU may provide a better synchrony between N availability and plant N demand, which minimizes the amount of time N is exposed to potential loss to the environment (Gandeza et al. 1991; Hopkins 2020; Hyatt et al. 2010; LeMonte et al. 2018; Munoz et al. 2005; Zvomuya and Rosen 2001; Zvomuya et al. 2003).

Of course, PCU is not without concern. Some studies have found that PCU can decrease crop yield if timing of application and release are not in line with crop need (Farmaha and Sims 2013; Golden 2009). Even if yields are the same or higher, the costs of this EEF are higher than uncoated urea. Any additional cost must be covered by additional crop value and/or reductions in management costs, such as reduced labor for in-season fertigation (Hopkins et al. 2007). Furthermore, there are recent concerns that the polymer coatings are contributing to microplastics contamination in soil and potentially water bodies (Alimi et al. 2018).

However, this EEF source has been shown to be effective with many species [e.g., Kentucky bluegrass (LeMonte et al. 2016), maize (Kaur et al. 2020), rice (Fageria and Carvalho 2014), wheat (Nash et al. 2012), and many other species (Hopkins 2020, Vegan et al. 2021)]. There have been many studies comparing PCU with traditional N sources in potato with none reporting a significant decrease in yield. Rather, all N responsive sites had yields that were similar (Bero et al. 2014; Cambouris et al. 2014, 2016; Clément et al. 2021; Gao et al. 2018; Ghosh et al. 2019; Hyatt et al. 2010; Wen et al. 2020; Wilson et al. 2009; Zebarth et al. 2012; Zvomuya et al. 2003) or increased (Chen and Hutchinson 2008; Chen et al. 2008; Gao et al. 2015; Hopkins et al. 2008; Hutchinson et al. 2003a b; Hutchinson 2005; Pack et al. 2006; Worthington et al. 2007; Ziadi et al. 2011; Zvomuya and Rosen 2001; Zvomuya et al. 2003;) with PCU. Other than a limited preliminary study as a precursor to this work (Hopkins et al. 2008), all these studies were conducted in relatively high rainfall/humidity climates with acid/neutral pH soils. Further work is needed to study PCU on the most commonly USA grown potato variety (Russet Burbank) in the semi-arid climate, with calcareous soils, of the Pacific Northwest, where a majority of potato is grown in the USA.

The objectives of this study were to compare the effects of a proven PCU and uncoated urea on Russet Burbank potato production under semi-arid, volcanic sand soil conditions in Idaho for yield, specific gravity, and internal defects. Taysom (2015) also reports results for plant N response [i.e., petiole NO_3-N, Normalized Difference Vegetative Index (NDVI), agronomic N efficiency] and changes in soil NO_3-N.

Materials and Methods

Three trials were conducted in commercial potato fields, evaluating the effectiveness of PCU [Environmentally Smart Nitrogen (ESN)®, Nutrien (formerly Agrium), Saskatoon, Saskatchewan, Canada] on Russet Burbank potato. The fields were in southern Idaho, USA near Blackfoot (Bannock loam) and two site years in Aberdeen (Declo loam). The soils were low in organic N and highly calcareous, with medium to high concentrations of most nutrients (Table 1). All fields were irrigated with 0.56–0.66 m water that contained 5–6 mg L^{-1} of NO_3^-N (total season N added through irritation was 28–39 kg N $ha^{-1)}$. The previous crop was spring wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) with approximately 2 Mg ha^{-1} of residual grain stubble incorporated into the soil shortly prior to planting.

Site selection was based on principles discussed by Thornton et al. (2007). Cooperating growers typically achieve above average potato yields and tuber quality and generally follow Best Management Practices (Hopkins et al. 2007; Miller and Hopkins 2007; Zebarth and Rosen 2007). Standard grower practices were followed to ensure N was the only likely limiting factor. It is noted that

Table 1 Pre-plant soil test data and nutrient levels for three Idaho research locations (Aberdeen site 1 2006 = AB1; Blackfoot 2006 = BF1; and Aberdeen site 2 2007 = AB2) for N fertilizer response trials on 'Russet Burbank' potato

	Location		
Soil Test Data[a]	AB1	BF1	AB2
Soil pH	8.4	8.0	8.3
Excess Lime, %	5.7	1.0	7.2
Organic Matter, %	1.7	1.8	1.4
Nitrate–N, mg kg^{-1}	1	5	7
Phosphorus, mg kg^{-1}	13	16	24
Potassium, mg kg^{-1}	170	160	215
Calcium, mg kg^{-1}	4168	2906	2365
Magnesium, mg kg^{-1}	267	401	352
Sodium, mg kg^{-1}	23	23	69
Sulfate-S, mg kg^{-1}	14	8	11
Zinc, mg kg^{-1}	1.2	1.8	1.4
Iron, mg kg^{-1}	5.0	9.6	2.5
Manganese, mg kg^{-1}	6.0	8.4	4.5
Copper, mg kg^{-1}	0.4	0.6	0.9
Boron, mg kg^{-1}	0.4	0.5	0.9

[a]Soil test methods include: 2:1 (pH), titration (Lime), Walkley–Black (OM), KCl (nitrate), bicarbonate Olsen (P), ammonium acetate (K, Ca, Mg, S, and Na), DTPA (Zn, Fe, Mn, Cu), and hot water (B) (Miller et al. 2013)

two additional trials were performed on growers' fields near Rupert, Idaho with the same treatments and methods (Taysom 2015). The data from these locations were omitted from data analysis because of a negative response to N fertilization. This was likely due to cooperating grower error with N contamination from the irrigation.

Individual plots were 3.6 m wide (four 0.91 m rows) by 12.2 m long with treatments established in a randomized complete block design with four replications. Thirteen treatments were evaluated, including: an untreated control and four rates of N applied as: 1) PCU (43-0-0) applied pre-emergence, 2) uncoated urea (46–0-0) applied pre-emergence, or 3) uncoated urea split-applied. The four rates of N were 33, 67, 100, and 133% of recommended N rate based on University of Idaho fertilizer recommendations for Russet Burbank potato using soil test values, yield potential, and previous crop information for each location (Hopkins et al. 2020). The recommended N rates for each field were within 10 kg N ha^{-1} of each other and, therefore, the rates were rounded up/down to be equivalent within a year. The N rates were 101, 202, 303, and 404 kg ha^{-1} for the first year and 90, 179, 269, and 359 kg ha^{-1} for the second year.

The pre-emergence applications occurred just prior to cultivation and stems breaking through the soil. This timing of the single application of PCU or urea was determined based upon research conducted at the University of Idaho (Hopkins et al. 2008) and the University of Minnesota (Wilson et al. 2009) showing that PCU applied before planting may release N too early for Russet Burbank potato needs and result in a substantial delay in tuber initiation and, thus, yield losses. The University of Minnesota data shows the N release curve from PCU closely followed that for plant N need when it was applied at plant emergence (Wilson et al. 2009). In this study, the treatments applied pre-emergence were incorporated into the soil 1–2 days after application. Cultivation occurred 16–23 days after planting at the end of May or early June.

The split-applied treatment at the 100% recommended rate represented the grower standard practice (GSP). The split-applied treatments had 50% of the N applied pre-emergence (as described previously), with the remainder applied in three equal applications throughout the growing season. Timing of the first in-season application was based on the University of Idaho's in-season N recommendations (Hopkins et al. 2020) derived using petiole NO_3^--N analysis of composite samples taken from non-harvest rows in the GSP plots.

Vines that did not naturally senesce were killed by mechanical defoliation on September 8–11. After sufficient time for skins to thicken, harvest occurred at the end of September or early October. Approximately 6.1 m of row were harvested from each of the center two rows of each plot. Tubers were stored in a controlled environment potato storage in burlap bags for 21 to 31 d until they could be graded for size, shape, internal/external defects, and specific gravity content based on US Department of Agriculture (USDA) potato grading standards (USDA 1998). Yield categories included: US No. 1, US No. 2, marketable (US No. 1 + US No. 2), under-sized (< 114 g), malformed, total culls (under-sized + malformed), and total yield (marketable + culls). The US No. 1 tubers were further parsed into size categories of 114–170, 170–284, 284–397, and > 397 g. After grading and weighing, a random sub-sample of four tubers was taken from each of the four US No. 1 size categories to evaluate specific gravity for each replicate (Kleinschmidt et al. 1984) and internal quality. For the internal analysis, the tubers were assessed for hollow heart and brown center on a percent incidence basis after cutting the tubers in half on the longitudinal axis.

Because of missing data points—due to a few plots being damaged from irrigation problems—the data was analyzed with analysis of variance using GLM (General Linear Model) with a $P = 0.05$ criteria using SAS (Version 9.1, SAS Institute, 2003, North Carolina, USA). Means were separated by LSD (Least Significant Difference) test with an alpha of 0.05.

Results

General Response

Not surprisingly, there were significant differences across locations, but the N response was similar across locations as there generally was a lack of a significant location interaction for most parameters (Table 2). Location (field) averages are in Table 3; Supplemental Tables 1-3.

The N rate effect was significant for nearly all measured parameters, with response similar across locations (Table 2). Yields were increased with N fertilization (Supplemental Tables 1–3). Regarding the yield parameters of greatest interest, the US No. 1 yield peaked numerically at the 33% and marketable and total yields at 67% of the recommended N rate. As the interactions were not significant for most parameters, results were combined across locations to show the general N response (Table 3). Additionally, N rate affected all tuber size categories (Table 2) with a general trend towards larger tubers as N rate increased (Table 3; Supplemental Tables 1-3). Specific gravity was also impacted by N rate (Table 2), with N rate decreasing specific gravity, with the unfertilized control significantly higher by 0.02 and 0.04 for the two middle and the highest N rates, respectively (Table 4).

Fertilizer Source

The impact of fertilizer source was the primary focus of this research and was significant for many yield and quality factors, with the response similar across locations (Table 2). Exceptions for the location interaction include US No. 2 and total yield (Table 2).

All of the fertilizer source treatments, averaged across rates, were significantly higher in total yield over the untreated control (Table 5). Additionally, PCU was higher than split applied urea at both Aberdeen locations and higher than urea applied at emergence for AB1. The Blackfoot field followed a similar trend for a general N response, although treatment effects were not significant between fertilizer sources.

The N rate by fertilizer source interaction was not significant for any parameter (Table 2) and, thus, results were combined across N rates for the discussion below. Fertilizer source affected total yield and several tuber quality parameters—mostly independent of N rate and location (Table 2). The PCU treated tubers had significantly greater US No. 1, marketable, and total yield than all other treatments and all fertilized treatments were significantly greater than the unfertilized control (Fig. 1). Surprisingly, there was no difference in yield response between the split-applied urea and urea applied all at emergence.

The only significant interaction between N rate and source across locations was for US No. 2 yield (Table 2; Supplemental Tables 1 and 3). At AB1, the PCU at the 100% rate was higher than all other treatments besides urea applied all at once at the 67% rate. At AB2, the PCU did not have more US No. 2 yield than the control, with only some of the urea treatments showing higher incidence of these lower quality category of tubers.

Tuber size, another important quality factor, was also impacted by fertilizer source (Table 2). All fertilized treatments resulted in significantly lower yields of the smallest tuber size (114–170 g) category (Fig. 2). In addition, the PCU fertilized treatment had significantly higher yield of the small tubers than the urea applied at pre-emergence. Further

Table 2 Significance ($P > F$) of overall model and model components including: block, location (L), N rate (R), fertilizer source (S), with all possible interactions on tuber yield parameters, specific gravity, and internal defects for three locations of a N fertilizer response trial with five N rates and four sources on 'Russet Burbank' potato

	Model	Block	L	R	S	L*R	L*S	R*S	L*R*S
Yield Parameters									
US No.–1—114–170 g	**< 0.0001**	**0.0283**	**< 0.0001**	**< 0.0001**	**0.0089**	**0.0072**	0.9347	0.6528	0.1538
US No.–1—170–284 g	**< 0.0001**	**0.0116**	**< 0.0001**	**0.0196**	0.1307	0.5110	0.7853	0.6085	0.4572
US No.–1—284–397 g	**< 0.0001**	0.3993	**< 0.0001**	**< 0.0001**	**0.0505**	0.2564	0.8481	0.0870	0.3480
US No. 1— > 397 g	**< 0.0001**	0.1222	**< 0.0001**	**< 0.0001**	**0.0019**	**0.0012**	0.7181	0.2660	0.6081
Total US No. 1	**< 0.0001**	**0.0049**	**< 0.0001**	**0.0022**	**0.0009**	0.2404	0.5961	0.7477	0.4869
US No. 2	**< 0.0001**	0.9688	**< 0.0001**	**< 0.0001**	0.2196	0.7072	**0.0309**	0.5425	**0.0363**
Marketable (US No. 1 + 2)	**< 0.0001**	**0.0027**	**< 0.0001**	**< 0.0001**	**0.0018**	0.4374	0.4430	0.9864	0.6579
< 114 g	**< 0.0001**	0.2841	**< 0.0001**	**< 0.0001**	0.2249	0.2471	0.2144	0.6627	0.9893
Malformed	**< 0.0001**	**0.0051**	**< 0.0001**	0.5684	0.0595	0.2151	0.6853	0.2725	0.7287
Culls (< 114 g + Malformed)	**< 0.0001**	**0.0214**	**< 0.0001**	**0.0415**	0.0863	0.4596	0.4399	0.2098	0.6162
Total Yield	**< 0.0001**	**0.0483**	**< 0.0001**	**< 0.0001**	**0.0003**	0.7841	**0.0077**	0.8039	0.7266
Specific Gravity and Internal Defects									
Specific Gravity	**< 0.0001**	0.1058	**< 0.0001**	**0.0003**	0.0975	**0.0024**	0.6312	0.1679	0.1014
Hollow Heart	0.1321	0.9078	0.0054	0.1935	0.0585	0.4135	0.2187	0.4453	0.6590
Brown Center	**< 0.0001**	0.2331	**< 0.0001**	0.1766	**0.0130**	0.2694	0.0668	0.7698	0.8442

Values in bold face type are significant at $P < 0.05$

Table 3 'Russet Burbank' potato yields (Mg ha^{-1}) as a function of nitrogen (N) rate (combined across three locations and three N sources)

Rate, %	US No. 1 114-170 g[a]	170-284 g	284–397 g	> 397 g[a]	Total	
0	6.2 a	8.4 b	1.9 c	0.7 c	17.3 b	
33	5.0 b	10.6 a	4.2 b	2.4 c	22.3 a	
67	4.1 c	9.9 ab	5.5 a	4.5 a	24.1 a	
100	4.1 c	9.3 b	5.0 a	4.3 a	22.7 a	
133	3.8 c	8.8 b	5.2 a	4.5 a	22.3 a	
Rate, %	US No. 2[a]	Marketable[b]	Culls < 114 g	Total Tuber Malformed	Total	Yield
0	7.7 b	25.1 c	6.7 a	5.2 a	11.9 a	37.0 c
33	8.7 b	31.0 b	4.9 b	6.8 a	11.7 a	42.7 b
67	10.6 a	34.7 a	3.9 cd	6.4 a	10.3 ab	45.0 a
100	10.8 a	33.5 a	4.0 c	6.7 a	10.7 ab	44.3 ab
133	11.3 a	33.6 a	3.4 d	6.3 a	9.8 b	43.4 ab

N rates within a category sharing the same letter(s) are not significantly different than one another. ($P < 0.05$)

[a]Note that there was a location by N rate interaction for the smallest and largest US No. 1 size categories and a location by N rate by N source interaction for US No. 2 tuber yield

[b]Marketable is the sum of total US No. 1 plus US No. 2 tuber yields

Table 4 Specific gravity and hollow heart and brown center percentages for three locations (AB1, BF1, AB2; Table 1) of a nitrogen (N) fertilizer response trial on 'Russet Burbank' potato to five rates of nitrogen (N) applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only)

	Specific Gravity			% Hollow Heart			% Brown Center		
Rate, %[a]	AB1	BF1	AB2	AB1	BF1	AB2	AB1	BF1	AB2
				unfertilized check					
0	1.086	1.082	1.083	10.9	14.1	3.1	0.0	1.6	3.1
				PCU at emergence					
33	1.083	1.081	1.083	6.3	6.3	4.7	0.0	0.0	17.2
67	1.080	1.084	1.082	7.8	9.4	0.0	3.1	1.6	21.9
100	1.080	1.086	1.082	9.4	6.3	4.7	6.3	3.1	18.8
133	1.077	1.082	1.081	6.3	0.0	4.7	0.0	1.6	21.9
				Urea at emergence					
33	1.082	1.086	1.084	14.1	1.6	9.4	1.6	1.6	12.5
67	1.082	1.086	1.083	9.4	4.7	9.4	0.0	1.6	10.9
100	1.078	1.083	1.080	6.3	3.1	0.0	0.0	0.0	9.4
133	1.081	1.083	1.079	17.2	4.7	3.1	1.6	0.0	12.5
				Split-applied urea[b]					
33	1.080	1.083	1.083	6.3	4.7	4.7	3.1	0.0	7.8
67	1.079	1.082	1.082	3.1	3.1	1.6	1.6	0.0	18.8
100	1.081	1.085	1.079	4.7	3.1	1.6	1.6	0.0	15.6
133	1.075	1.083	1.081	3.1	1.6	3.1	1.6	1.6	9.4
				Average across all treatments					
	1.080	1.083	1.082	8.1	4.8	3.8	1.6	1.0	13.8

There were no statistically significant interactions for N rate and source for individual parameters or treatments across locations

[a]Recommended N rate of 100% based on yield goal, residual N, soil type, etc. equaled = 303 kg ha^{-1} for AB1, and BF1 and 269 kg ha^{-1} for AB2

[b]Urea applied as 50% at emergence with remaining applied in three uniform rates during the season

Table 5 Total yields (Mg ha^{-1}) for a fertilizer trial at three locations (AB1, BF1, AB2; Table 1) of a nitrogen (N) fertilizer response trial on 'Russet Burbank' potato. Results are averaged across four N rates applied as polymer coated urea (PCU) or urea applied at emergence or split applied (urea only)

	AB1	BF1	AB2
Unfertilized check	35.9 c	32.8 b	42.1 c
PCU at emergence	46.7 a	38.3 a	51.5 a
Urea at emergence	40.0 b	37.4 a	50.1 ab
Split-applied urea	41.9 b	39.0 a	47.5 b

Treatments within a location column sharing the same letter(s) not significantly different than one another. ($P < 0.05$)

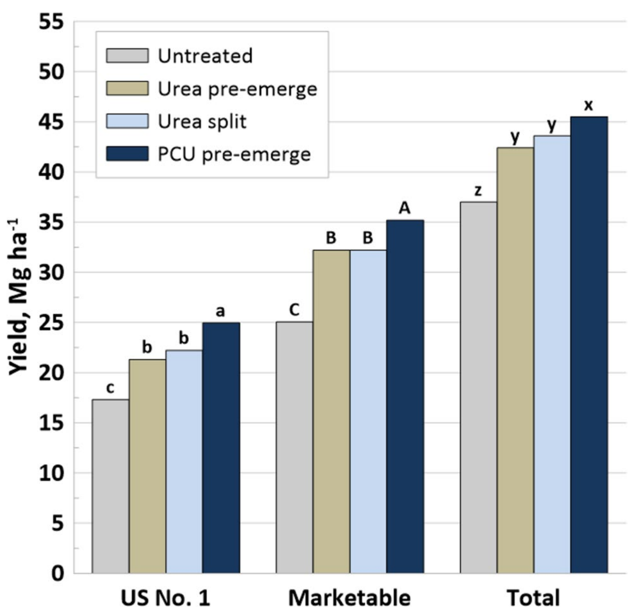

Fig. 1 US No. 1, marketable, and total 'Russet Burbank' potato yield averaged across three locations and four N rates for N sources [urea applied pre-emergence, urea split applied, or polymer coated urea (PCU)] compared to an untreated control. Bars within each group with the same letters are not significantly different from each other. ($P < 0.05$)

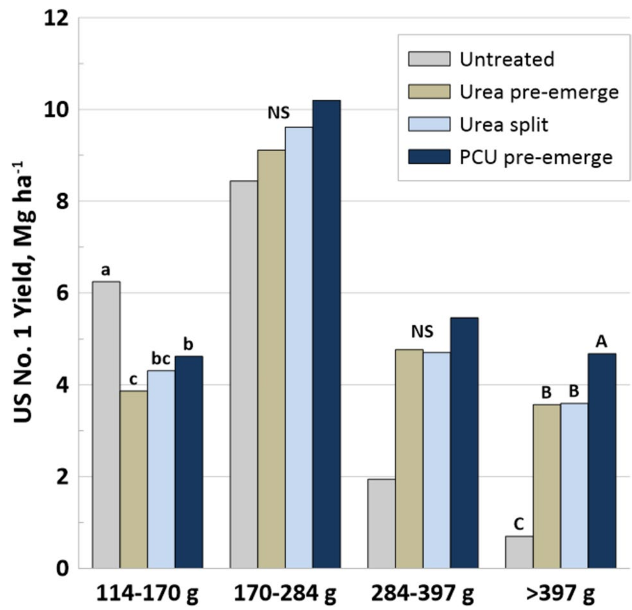

Fig. 2 US No. 1 'Russet Burbank' potato tuber yield, by tuber size, averaged across three locations and four N rates for N sources [urea applied pre-emergence, urea split applied, or polymer coated urea (PCU)] compared to an untreated control. Bars within each group with the same letters are not significantly different from each other. ($P < 0.05$)

evidence of the size shift is shown with a highly significant increase in the yield of the largest sized tubers (> 397 g), with the PCU fertilized tubers having higher yield than both urea treatments. Furthermore, all fertilized treatments produced higher yields of large tubers than the unfertilized control. A similar trend was observed with the next highest size category (284–397 g). Although not significant, PCU showed a trend of increasing tuber yields with the 170-284 g size category, similar to the upper two size categories (Fig. 2).

Other quality parameters were also affected by fertilizer source. The model was not significant for hollow heart incidence, but it was highly significant for brown center (Table 2). The incidence of brown center was higher for the PCU fertilized treatment than other fertilizer sources, which were not statistically different from the unfertilized control (Fig. 3). Specific gravity and yields of US No. 2 and cull tubers were not affected by fertilizer source (Table 2).

Discussion

The results of this study show that application of PCU at emergence is an effective method and source for Russet Burbank potato fertilization under conditions of low rainfall/humidity and calcareous alkaline soils. The Russet Burbank variety makes up the majority of potato grown in the USA. It is known to have relatively poor rooting depth and effectiveness. The yield increases measured (Fig. 1) are similar to a preliminary study with Russet Burbank conducted under similar conditions where PCU resulted in significant increases of 5.6, 5.3, and 4.4 Mg ha^{-1} over a single application of urea (both applied at hilling) for US No. 1, marketable, and total yield, respectively (Hopkins et al. 2008). In that study, the PCU also yielded better than the split applied urea (GSP) for US No. 1 yield (3.5 Mg ha^{-1}). In slight contrast to this study, a reduced rate of PCU was found to be as effective as the full rate of split applied urea. Chen and Hutchinson (2008) did not measure greater yields ('Atlantic') with PCU, but also found that a reduced rate of PCU yielded similarly as a full rate of traditional N fertilizer.

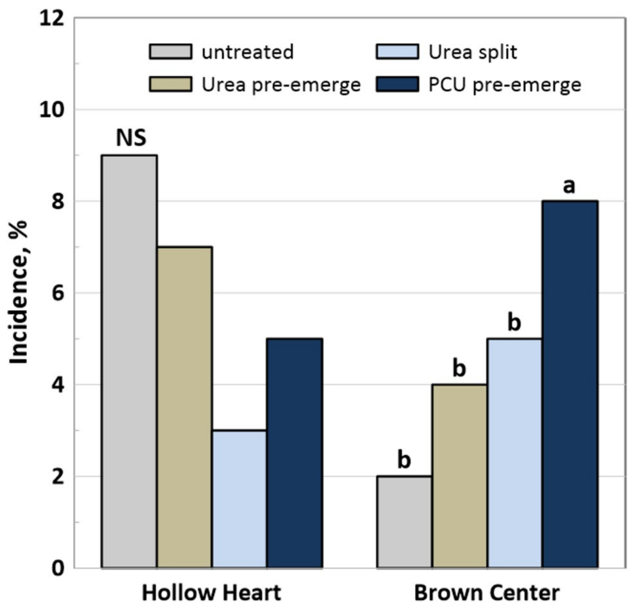

Fig. 3 US No. 1 'Russet Burbank' potato tuber hollow heart and brown center physiological disorders incidence averaged across three locations and four N rates for N sources [urea applied pre-emergence, urea split applied, or polymer coated urea (PCU)] compared to an untreated control. Bars within each group with the same letters are not significantly different from each other. ($P < 0.05$)

In comparison to research in high rainfall/humidity regions, the yield results in this study (Fig. 1) and Hopkins et al. (2008) are similar to others showing yield increases with PCU applied to potato (Chen et al. 2008; Gao et al. 2015; Hopkins et al. 2008; Hutchinson et al. 2003a, b; Hutchinson 2005; Pack et al. 2006; Worthington et al. 2007; Ziadi et al. 2011; Zvomuya and Rosen 2001; Zvomuya et al. 2003). Other researchers found no increase with PCU (Bero et al. 2014; Cambouris et al. 2016; Clément et al. 2021; Gao et al. 2018; Ghosh et al. 2019; Hyatt et al. 2010; Wen et al. 2020; Wilson et al. 2009; Zebarth et al. 2012; Zvomuya et al. 2003). However, there are no published reports with a definitive decrease in yield with PCU applied to potato, including with Gao et al. (2017) and with two sites in our study (Taysom 2015) where there was no response to N fertilization. Most of these studies also used the indeterminate, late maturing Russet Burbank cultivar, although several used determinate, mid-season maturing Atlantic cultivar (Chen et al. 2008; Hutchinson et al. 2003a, b; Hutchinson 2005; Pack et al. 2006; Worthington et al. 2007); while others used other cultivars of 'Chieftain' and 'Goldrush' (Ziadi et al. 2011), 'Favorita' (Gao et al. 2015), and 'Dakota' (along with Russet Burbank; Ghosh et al. 2019). Response to PCU could vary by cultivar depending on whether they are indeterminate or determinate, length of maturity, and rooting depth and uptake efficiency. Some cultivars have much better root systems than others and this would likely be a primary impact on PCU effectiveness (Hopkins and Hansen 2019; Hopkins 2020).

The reasoning for yield increases where measured is possibly two-fold. First, it has been demonstrated that, in contrast to uncoated urea, the N release from PCU closely matches the N uptake needs of Russet Burbank potato under field conditions (Cambouris et al. 2016; Wilson et al. 2009). Secondly, PCU has been found to reduce N loss from NO_3^- leaching, N_2O emission, and NH_3 volatilization (Alva 1992; Clément et al. 2021; Errebhi et al. 1998; Gao et al. 2017; Hopkins 2020; Hyatt et al. 2010; LeMonte et al. 2016, 2018; Mikkelsen et al. 1994; Prunty and Greenland 1997; Ruser et al. 1998; Shoji and Kanno 1994; Venterea et al. 2011; Wang and Alva 1996; Wilson et al. 2010; Worthington et al. 2007; Zebarth et al. 2012; Zvomuya et al. 2003). This often results in increases in NUE (Errebhi et al. 1999; Gao et al. 2015; Kitchen et al. 2022; Shoji et al. 2001; Trenkel 1997).

Regarding N release from PCU closely matching plant needs, there is only a slight, non-significant trend that this was a primary reason for the yield increases measured in this study (Supplemental Tables 1–3; Fig. 1). If so, the split applied urea should have had significantly greater yield than urea applied all at once, which would be normally expected. Other research has also shown no benefit to split applications of N in certain conditions (Zebarth and Rosen 2007). Nevertheless, this contrasts with the findings of others that a steady supply of N is a best management practice for both yield and environmental protection (Errebhi et al. 1998; Gayler et al. 2002; Hopkins et al. 2008, 2020; Joern and Vitosh 1995b; Prunty and Greenland 1997; Munoz et al. 2005; Ruser et al. 1998; Saffigna et al. 1977; Singh and Sekhon 1976; Waddell et al. 1999, 2000; Westermann and Kleinkopf 1985; Westermann et al. 1988).

Regarding reduced N loss to the environment, we did not directly measure these in this study. Others have found reduced NO_3^- leaching, N_2O loss, and/or NH_3 volatilization with increased N uptake with PCU applied to potato compared to traditional N sources (Bero et al. 2014; Cambouris et al. 2016; Clément et al. 2020, 2021; Gao et al. 2015; Ghosh et al. 2019; Hutchinson et al. 2003b; Hyatt et al. 2010; Munoz et al. 2005; Perron et al. 2019; Venterea et al. 2011; Wilson et al. 2010; Ziadi et al. 2011; Zvomuya et al. 2003), although others have shown that reduced loss of N to the environment does not always take place and is highly dependent upon variable weather and field conditions (Clément et al. 2021; Gao et al. 2017; Zebarth et al. 2012). A lack of conditions resulting in N loss may result in a lack of benefit for PCU over traditional N sources.

In this study, there was very little in-season precipitation (< 0.1 m). However, the soils were relatively sandy and crops heavily irrigated (~ 0.1 m week^{-1}). Potato, especially Russet Burbank, has a very shallow, inefficient root system and a relatively high-water requirement (Fixen and

Bruulsema 2014; Hopkins et al. 2014, 2020; Hopkins and Hansen 2019; Munoz et al. 2005). The result of high rates of irrigation on the sandy soil with poor root efficiency could have contributed to N loss by leaching and, thus, a possible reason for the increased yields with PCU over urea.

In addition to yield, tuber size can be important to growers because of incentives or disincentives for tubers greater than 170 g. Our results showed a size shift between the US No. 1 tuber categories, with a trend for larger tubers with PCU (Fig. 2). Other studies have shown similar results (Worthington et al. 2007; Ziadi et al. 2011; Zvomuya and Rosen 2001; Zvomuya et al. 2003). However, Wilson et al. (2009) showed increased tuber size as a function of N rate, but no significant impacts with PCU.

The effects of PCU on internal quality have not been widely investigated and results are mixed. Hollow heart can depend on year, weather patterns and tuber size. In general, hollow heart affects larger tubers (Beattie 1989), which tend to be increased proportional with N rates. Wilson et al. (2009) showed that split-applied soluble N had the highest incidence of hollow heart but was only statistically different from the lowest soluble N level and the unfertilized check. In addition, the split-applied soluble N was statistically similar to most PCU applied treatments. Our results for hollow heart were not significant (Fig. 3), but there was an opposite trend with the control without N having numerically higher hollow heart incidence than the fertilized treatments. However, we found a significant increase in brown center, a precursor to hollow heart, with the use of PCU (Fig. 3). As with our results, Zvomuya and Rosen (2001) did not see an effect of N rate on hollow heart incidence, but brown center was not reported in their studies.

Bélanger et al. (2002) found that specific gravity was affected by N fertilization, with low specific gravity being tied to excessive N. Zvomuya and Rosen (2001) showed an opposite effect, with a significant increase in specific gravity when N rate was doubled from 140 to 280 kg N ha^{-1}. Wilson et al. (2009) and Ziadi et al. (2011) did not see an effect of N fertilization on specific gravity. Specific gravity results in our study were similar to Bélanger et al. (2002) but were not affected by N source (Table 2). Worthington et al. (2007) showed a significant decrease in specific gravity using a reduced rate of PCU compared to the ammonium nitrate fertilizer standard in one of two years, although the difference was slight. Zebarth et al. (2012) showed only minor difference in specific gravity regarding source.

Another objective of our work was to determine if less fertilizer can be used when using PCU in place of urea. As shown previously, N rate effects were highly significant for most measured yield parameters (Table 2). However, the response was similar across all fertilizer sources, as evidenced by a lack of a significant rate x source interaction. This contrasts the findings of Hopkins et al. (2008) and that of Chen et al. (2008) that found that a lower rate of PCU can be used in contrast to traditional N sources.

It is interesting to note in our study that each N source curve peaks at nearly the same N rate (data not shown); regression analysis of each of the PCU, urea split, and urea pre-emerge curves shows R^2 values of 0.9884, 0.9572, and 0.8866, respectively with peaks at 87, 85, and 90% of the recommended N rate, respectively, and these differences were not significant ($P > F$ 0.8754). These results suggest that the fields may have been slightly over-fertilized. More importantly, it is apparent that the N rate does not need to be adjusted when using PCU even though we see higher yields as stated in the results above. Fertilizer sources (urea applied pre-emergence or split applied and PCU) produced similar N responses, but the magnitude of the response may be slightly greater for PCU. This agrees with the idea of "spoon feeding" the potato crop by supplying a steady supply of N throughout the growing season in order to maximize yield and tuber quality (Errebhi et al. 1998; Gayler et al. 2002; Hopkins et al. 2020; Joern and Vitosh 1995b; Munoz et al. 2005; Prunty and Greenland 1997; Ruser et al. 1998; Saffigna et al. 1977; Singh and Sekhon 1976; Waddell et al. 2000; Westermann and Kleinkopf 1985; Westermann et al. 1988).

It is noteworthy that this study originally included two additional field locations that were likely compromised by inadvertent injection of N fertilizer into the irrigation water by the cooperating grower, which is why they were not included in this analysis. However, these data are reported by (Taysom 2015). There was no increase in yield due to N response at these locations and yields generally decreased with the increasing N rate, which provides evidence of the excess N. However, the PCU fertilized plots tended to have higher yields than the unfertilized check at the 33% and 67% rates, whereas yields for the urea fertilized plots were equal to or lower than the unfertilized check. It appears that the PCU resulted in less of a negative impact when excess N was present.

Only the agronomics, and not economics, of PCU were evaluated in this study. Of course, the economics of crop production, including fertilizer costs, is essential for farm and societal sustainability (Hopkins et al. 2007). When controlled release N fertilizers were first introduced with potato they did not perform as well as standard N products or soluble forms of N and were unpredictable in their release (Liegel and Walsh 1976; Waddell et al. 1999). Also, in the past, PCU fertilizers were too expensive to be economically feasible (Trenkel 1997; Zvomuya and Rosen 2001). Improvements in the polymer coating of new generation PCUs results in reduced costs of manufacturing, as well as N release rates similar to the uptake patterns of plants (Trenkel 1997), especially for potato (Wilson et al. 2009). It is noteworthy that, compared with the GSP (split application of urea), the use of PCU would reduce the need for additional applications, while maintaining or sometimes increasing yield parameters. This would decrease labor and fertigation expenses, which may help to counteract the inevitable higher costs of PCU.

The PCU product used in this trial has been engineered with a sophisticated coating of uniform thickness, which theoretically provides more consistent results. It should be noted that we have observed that not all PCUs are as effective as the ESN used in this trial (data not shown) and these data should not be extrapolated to other PCU products. Besides being a consistent product, it is relatively low in cost compared to early generation PCUs. We conducted an informal survey and found that farmers were paying 20–50% more for this PCU than uncoated urea (it is not uncommon to see costs more than 200% in the past). Results in this trial suggest that this additional cost could be covered by increases in tuber yield and quality—depending on current market rates.

Conclusion

The PCU fertilizer used in this study (ESN) applied at emergence resulted in US No. 1, marketable, and total yield increases and a size shift towards larger tubers compared to uncoated urea. However, the incidence of brown center increased as a function of increased tuber size. These data suggest that PCU can supply 'Russet Burbank' potato with a steady supply of N throughout the vegetative portion of the growing season. These data support the work of other researchers that show that PCU results in similar or greater potato yields. Our findings are unique in that this study was conducted in a low rainfall/humidity climate on calcareous soils, in contrast to all others conducted in relatively higher rainfall/humidity with acid/neutral pH soil. Our data suggests that, at similar fertilizer rates, PCU fertilizer was more efficient than immediately soluble urea-N in supplying N to Russet Burbank potato. The PCU fertilizer has a higher cost than uncoated urea. Whether it is economically viable depends on current market prices for urea, PCU, and potato. One factor that needs to be considered in the economic analysis is the fact that PCU is applied in a single application, whereas the grower standard practice (GSP) often includes multiple labor-intensive fertilizer applications. Using PCU in situations where in-season applications are not possible is especially appealing to growers

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Data Availability Raw data for this trial is available upon request once a companion economics paper is published.

Declarations

Conflict of Interest All authors declare that they have no competing interests that are directly or indirectly related to the work submitted for publication.

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