On-Farm Evaluation of Potato Response to Nitrogen Source and Rate and Length of History of Potato Cultivation

Carl Rosen, James Crants, and Matt McNearney
Department of Soil, Water, and Climate, University of Minnesota
crosen@umn.edu

Summary

A field experiment was conducted near Park Rapids, MN, in adjacent center pivot fields planted with Russet Burbank potatoes, to evaluate N fertilization strategies. The objectives of the study were (1) to find the optimum N application rate for this site (2) to evaluate different sources of N (3) to determine the effect of DCD, a nitrification inhibitor, on the value of uncoated urea as a N source for potatoes, and (4) to determine the effect of field planting history on the response of potato yield and tuber quality to N source and application rate. The response variables included tuber yield and size distribution, tuber quality, plant stand in mid July, and soil water NO_3-N concentration throughout the season. Ten treatments were applied in a randomized complete block design with four replicates. The effect of N application rate was evaluated by applying Environmentally Smart Nitrogen (ESN, Agrium, Inc.) at six rates at hilling just prior to emergence (0, 80, 120, 160, 200, and 240 lbs·ac^{-1} N). In addition to ESN, four other N sources were applied in treatments receiving 120 lbs·ac^{-1} N at hilling: urea, ammonium sulfate, SuperU (Koch Agronomic Services), and urea with dicyandiamide (DCD), a nitrification inhibitor. The study design was applied to adjacent fields under center-pivot irrigation. The old field was in its 15th year of potato cultivation, while the new field was in its second. In addition to the N applied at hilling, all treatments received 110 lbs·ac^{-1} N at other times in the old field and 108 lbs·ac^{-1} N in the new field. Soil water NO_3-N concentration tended to increase with N application rate in the new field, but not in the old field. N application rate significantly affected tuber yield, which peaked at rates of 160 – 200 lbs·ac^{-1} N as ESN at emergence (270 – 310 lbs·ac^{-1} N total) in both fields. The proportion of yield represented by larger size classes (over 6 or 10 ounces) increased with application rate across the range of rates tested. Tuber specific gravity decreased with increasing N application rate in the new field, but not in the old, and the same was true of plant stand. The source of N applied was less consequential than the application rate. SuperU produced higher soil water NO_3-N than urea in mid June, but there were no other effects of N source on any variable measured. The new field had a higher mean soil water NO_3-N concentration than the old in early to mid June, but a lower concentration from late June onward. There was a tendency for the old field to produce more very large tubers (> 14 oz) and fewer unusable tubers than the new field. Among the treatments used to evaluate the effect of N rate, the old field also had a higher mean tuber specific gravity than the new field. Overall, the effect of N application rate was much stronger than the effects of N source or field age, and we found no evidence that adding DCD to urea had any significant effect on its performance as a fertilizer. In previous years, the effects of field age have been more pronounced. The "new fields" used in those years were in their first seasons of potato cultivation, and it is possible that the effects of planting in a new field fade rapidly after the first year in potato production.

Background

Polymer coated ureas (PCUs) are controlled-release N fertilizers with a polymer coating that slows the diffusion of water into and urea out of urea granules. This reduces the risk of damaging seedlings with excessive ammonia (to which urea is initially converted by soil microbes) and losing N to volatilization of ammonia and leaching of nitrate (produced from ammonia by nitrification) before can take it up. In ten years of study at the Sand Plain Research Farm in Becker, Minnesota, Environmentally Smart Nitrogen (ESN, Agrium, Inc.: 44-0-0) has been found to be an effective N source for potatoes. It is not known, however, how relevant results at this site are to potato agriculture in other places.

In this study, we evaluated ESN in a field near Park Rapids, MN, approximately 120 miles NNW of Becker. ESN was tested at six different rates (0, 80, 120, 160, 200, and 240 $lbs{\cdot}ac^{-1}$ N) and compared with four other N sources at one of these rates (120 $lbs{\cdot}ac^{-1}$ N). The other sources were uncoated urea, ammonium sulfate, SuperU, and urea with dicyandiamide (DCD), a nitrification inhibitor. The products were applied at hilling, in addition to approximately 110 $lbs{\cdot}ac^{-1}$ N at planting and post-hilling.

A field's agricultural history potentially affects crop performance and the optimum rates and sources of N. To examine these effects, this study was conducted on in two adjacent center pivot fields. The "old field" had a 14-year history of potato cultivation, while the "new field" was in its second year of potato cultivation.

The objectives of this study were (1) to find the optimum application rate of N for Russet Burbank potatoes in fields near Park Rapids, MN, (2) to evaluate different N sources, including ESN, in these fields (3) to determine the effect of DCD on the value of uncoated urea as a N source for potatoes, and (4) to determine the effect of field planting history on the response of potato yield and tuber quality to N source and application rate.

Materials and Methods

The study was conducted in 2015 in two adjacent center-pivot-irrigated fields (Wade Kemper and Lil Wade) near Park Rapids, MN, in a Verndale-Nymore soil complex, using the potato cultivar Russet Burbank. The "new field" was planted on soil with a sandy texture (Verndale sandy loam) in an area that had had 1 previous potato crop. The "old field" was planted on similar soil (Verndale sandy loam and Nymore loamy sand) in an area that had had 14 previous potato crops. Characteristics of the top 10 inches of soil at planting are presented for each field in Table 1.

Within each field, ten treatments, as shown in Table 2, were established in a randomized complete block design with four replicates (40 plots per field). Russet Burbank B seed with an average size of 2.1 oz was planted on April 28 with 3-foot spacing between rows and 14-inch spacing within rows. Plots 50 feet long and 18 feet (6 rows) wide were marked on May 8. The fields were hilled on May 23 just prior to emergence. Shoot emergence occurred around May 28. Tubers harvested for analysis were collected from the central 20 feet of the middle two rows of each plot.

The new and old fields received, respectively, 675 and 418 $lbs{\cdot}ac^{-1}$ KCl (0-0-60) in the fall of 2014 (405 and 251 $lbs{\cdot}ac^{-1}$ K_2O, respectively). At planting (April 28), the new field received 68 $lbs{\cdot}ac^{-1}$ N, 52 $lbs{\cdot}ac^{-1}$ P_2O_5, 33 $lbs{\cdot}ac^{-1}$ S, and 1.1 $lbs{\cdot}ac^{-1}$ B as a mixture of urea (60 $lbs{\cdot}ac^{-1}$), AMS (138 $lbs{\cdot}ac^{-1)}$, MAP (100 $lbs{\cdot}ac^{-1}$), and 15% boron (7 lbs/ac). The old field received 67 $lbs{\cdot}ac^{-1}$ N, 24 $lbs{\cdot}ac^{-1}$ S, and 1.1 $lbs{\cdot}ac^{-1}$ B as a mixture of urea (100 $lbs{\cdot}ac^{-1}$), ammonium sulfate (100 $lbs{\cdot}ac^{-1}$), and 15% boron (7 lbs/ac). Each field received N as fertigations with UAN (32-0-0) on June 22 and 29. The new field received 5.4 $gal{\cdot}ac^{-1}$ (19 $lbs{\cdot}ac^{-1}$ N) on June 22 and 6.1 $gal{\cdot}ac^{-1}$ (21 $lbs{\cdot}ac^{-1}$ N) on June 29. The old field received 7.0 $gal{\cdot}ac^{-1}$ (25 $lbs{\cdot}ac^{-1}$ N) on June 22 and 5.4 $gal{\cdot}ac^{-1}$ (19 $lbs{\cdot}ac^{-1}$ N) on June 29. In total, the new field received 108 $lbs{\cdot}ac^{-1}$ N and the old field received 110 $lbs{\cdot}ac^{-1}$ N as a baseline rate.

Study treatments differed in the amount and form of N applied at emergence hilling (May 22). Five treatments received 80, 120, 160, 200, or 240 $lbs \cdot ac^{-1}$ N as ESN, and four treatments received 120 $lbs \cdot ac^{-1}$ N as urea, ammonium sulfate, Super U, or urea with dicyandiamide (DCD), a nitrification inhibitor. A control treatment received no fertilizer at hilling.

Suction tube lysimeters were installed on May 8 and 13 in the new and old fields, respectively, to sample soil water at a depth of 4 feet. In each of the two fields, the lysimeters were placed in each plot in treatments 1, 3, and 6 – 10. Samples were collected on May 22 and 27, June 3, 10, 17, and 24, July 1, 8, 15, 22, and 29, August 10 and 19, and September 22. The samples were stored frozen and then tested for NO_3-N concentration. Lysimeters were installed in plots receiving 0, 120, or 240 $lbs \cdot ac^{-1}$ N at hilling as ESN (treatments 1, 3, and 6) and those receiving 120 $lbs \cdot ac^{-1}$ N at hilling as urea, ammonium sulfate, SuperU, or urea with DCD (treatments 7-10).

From May 27 through September 24, rainfall was monitored on-site, and overhead irrigation was applied as needed. Daily precipitation in this period is presented in Figure 1. Precipitation data from May 6 through May 26 was collected on-site by the grower (R. D. Offutt Company). Data from April 28 through May 5 come from the National Weather Service weather station in Park Rapids. Plant stand counts were conducted on the central 20 feet of the two harvest rows in each plot on July 10, 48 days after hilling. Petioles were collected on July 1, July 10, July 20, July 29, and August 7. The petiole of the 4^{th} leaf from the end of a shoot was sampled from 25 plants per plot. Samples will be analyzed for NO_3-N concentration on a dry-weight basis with a Wescan N analyzer.

Tubers were harvested on September 23 and 24, and cleaned, sorted, and graded as soon as possible afterward. About 2.1% of harvested tubers were classified as "unusable," including those with serious internal defects. These were included in total yield, but not in other summary variables. Specific gravity was determined for a subset of marketable tubers from each plot.

To assess residual soil NO_3-N and NH_4-N concentrations after harvest, 12-inch soil cores were collected from each plot on October 13. These were analyzed for NO_3 and NH_4 concentrations using a Wescan N analyzer.

ANOVA tests were performed using the GLM procedure in SAS 9.4. To evaluate the effect of ESN application rate at hilling, analyses were performed on treatments 1 – 6, using field, ESN rate, replicate, and field*rate as independent variables. The effect of rate was also evaluated using linear and quadratic contrasts. To evaluate the effect of N source, analyses were performed that included only treatments 3 and 7-10, with field, N source, replicate, and field*source as independent variables. Where the field*rate or field*source interaction was not significant, Waller-Duncan k-ratio t-tests were performed on all significant results for the main effect of rate or source to determine the minimum significant difference between treatments.

Results:

Soil water NO_3-N

Results for soil water NO_3-N concentration 4 feet below the soil surface are presented in Table 3. Soil water NO_3-N concentration increased over time from May 22 to June 10 (new field) or June 24 (old field).

The relationship of soil water NO_3-N to N application rate (treatments 1, 3, and 6, Table 3a) differed between the two fields. In the new field, soil water NO_3-N increased with application rate on most sampling dates, though this relationship was not consistently significant and was not always evident. In the old field, there was rarely a significant relationship between N application rate and soil water NO_3-N, and on the only three dates when a relationship was present (July 8, July 15, and August 10), the treatment receiving the intermediate application rate (120 $lbs \cdot ac^{-1}$ N; treatment 3) had the highest soil water NO_3-N concentration.

N source (treatments 3, 7 – 10, Table 3b) was not generally related to soil water NO_3-N. Only on June 10 and 17, and only when both fields were considered together, was there a relationship. On those dates, the treatment receiving Super U (treatment 9) had higher soil water NO_3-N than the treatment receiving urea (treatment 7). On June 17, it also had higher soil water NO_3-N than the treatments receiving ESN (treatment 3) or urea with DCD (treatment 10). Field age was often a significant factor in soil water NO_3-N concentration, with the old field generally having higher concentrations than the new field. Only among the treatments receiving different N sources at a constant rate (treatments 3, 7 – 10) on June 3 did the new field have higher soil water NO_3-N than the old field.

Tuber yield and size

Results for tuber yield in the study plots are presented in Table 4. Outside of the study plots, the new field yielded 517.3 $cwt \cdot ac^{-1}$ and the old field yielded 500.2 $cwt \cdot ac^{-1}$. In the analyses of the effects of N application rate (Table 4a), there were significant effects of the rate*field interaction term for total yield, usable yield, yield of U.S. No. 1 tubers, and marketable yield (all of which were closely related to each other). The significance of this interaction is attributable to high yield at 160 $lbs \cdot ac^{-1}$ N as ESN and low yield at 200 $lbs \cdot ac^{-1}$ N as ESN in the old field relative to the new. The two fields had very similar yield at all other application rates.

For treatments in the N rate study (treatments 1 – 6, Table 4a), the old field had higher yield of tubers over 14 ounces than the new. N application rate significantly influenced multiple tuber yield variables (Table 4a). The percentage of yield in tubers over 6 or 10 ounces increased steadily with application rate, as did the absolute yield of tubers over 14 ounces. In both the new and old fields, total yield, marketable yield, and yield of U.S. No. 1 tubers were low in the control treatment (treatment 1) and not consistently responsive to application rate among the treatments receiving any amount of ESN at hilling (treatments 2 – 6).

Among the treatments included in evaluating the effect of N source (treatments 3 and 7 – 10, Table 4b), there were almost no significant effects of N source, field age, or their interaction. The only exception was an effect of field age on the yield of unusable tubers, which was higher in the new field. (Unusable tubers are tubers of low quality, discussed further in the following section.)

Plant stand and tuber quality

The tuber quality results are shown in Table 5. Plant stand on July 10 was weakly negatively related to the application rate of ESN ($0.05 < P < 0.10$; treatments 1 – 6, Table 5a), with a significant linear contrast of stand against application rate ($p < 0.05$). This trend was evident in the new field (linear contrast $P < 0.05$), but not in the old field ($P > 0.10$). Plant stand was not related to N source (treatments 3, 7-10, Table 5b).

Among the treatments receiving different rates of ESN at hilling (treatments 1-6), tuber specific gravity was higher in the old field than the new, and it decreased with increasing N application rate. A larger proportion of the yield was unusable for reasons other than hollow heart or brown center in the new field, and this proportion tended to decrease with increasing N application rate.

Among the treatments receiving different sources of N at a uniform rate (treatments 3, 7 – 10), a larger proportion of yield was unusable for reasons other than hollow heart or brown center in the new field than the old, and the new field also had somewhat higher prevalences of both hollow heart and brown center. The greater proportion of unusable yield in the new field is probably not attributable to a higher prevalence of disease, since the two soil pathogens tested for (*Verticillium* and lesion nematodes) were much less abundant in the new field (Table 1).

Conclusions

The N application rate had significant effects on multiple yield variables. Total and marketable yield peaked at a total application rate of 270 – 310 lbs·ac^{-1} N (160 – 200 lbs·ac^{-1} N as emergence applied ESN) in both fields. The proportion of yield in tubers over 6 or 10 ounces increased with application rate across the range of rates tested, though with diminishing returns at higher rates. In contrast, the source of N used and the age of the field had few significant effects on yield variables in this season of the study.

The lack of any effect of N source is similar to results obtained from this study in 2013, when the sources evaluated were urea, ammonium sulfate, ESN, and a blend of ESN and Duration (a slower-release PCU than ESN). However, in 2014, N source influenced tuber yield (low for urea and Agrocote, which was 100% 44-0-0 that year, relative to ammonium sulfate, ESN, and ESN with Duration, with ESN producing especially high marketable yield), tuber size (low for urea), and the prevalence of hollow heart (low for ESN, but high for ESN with Duration). The cause of the inconsistency in the effect of N source from year to year is unclear, particularly since the two sources producing the most divergent results in 2014 (urea and ESN) were included in the study in all three seasons.

The effects of field age on tuber size and quality were less pronounced in 2015 than they have been in previous seasons. This may be a reflection of the age of the "new" field. In 2013 and 2014, the new field was in its first year of potato production. In 2015, the new field was in its second year of potato production. It is possible that the some of the effects of field age seen in previous years are very short-lived.

Table 1. Initial soil characteristics in each of the two study fields near Park Rapids, MN, in 2015.

Field	OM (%)	pH	CEC	Bray P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	S (ppm)	Zn (ppm)	Mn (ppm)	Fe (ppm)	Cu (ppm)	B (ppm)	Sand (%)	Silt (%)	Clay (%)	*Verticillium* propagules per g soil	Lesion nematodes per g soil
New	1.8	5.8	8.8	63	130	169	1045	16.0	2.1	11.3	54	0.57	0.33	80	15	5	1	21
Old	1.7	6.1	9.0	107	175	226	1070	19.7	3.6	6.3	68	0.60	0.43	84	13	3	24	162

Table 2. N treatments tested on irrigated Russet Burbank potatoes near Park Rapids, MN, in 2015.

Treatment	Nitrogen source[1] at emergence	Nitrogen application rate at emergence (lbs·ac^{-1})	Total nitrogen application rate (lbs·ac^{-1})
1	Control	0	110
2	ESN	80	190
3	ESN	120	230
4	ESN	160	270
5	ESN	200	310
6	ESN	240	350
7	Urea	120	230
8	AS	120	230
9	SuperU	120	230
10	Urea + DCD	120	230

[1]Ammonium sulfate: 21-0-0. ESN (Environmentally Smart Nitrogen; Agrium, Inc.): 44-0-0. Urea, SuperU (Koch Agronomic Services): 46-0-0.

Figure 1. Inches of precipitation received as rainfall and irrigation between April 28 and September 24, 2015, in the study fields near Park Rapids, MN. Data for April 28 to May 5 were obtained from the National Weather Service weather station in Park Rapids. Data were collected by RD Offutt from May 6 to May 27. Data from May 27 to September 24 come from a weather station in the new field.

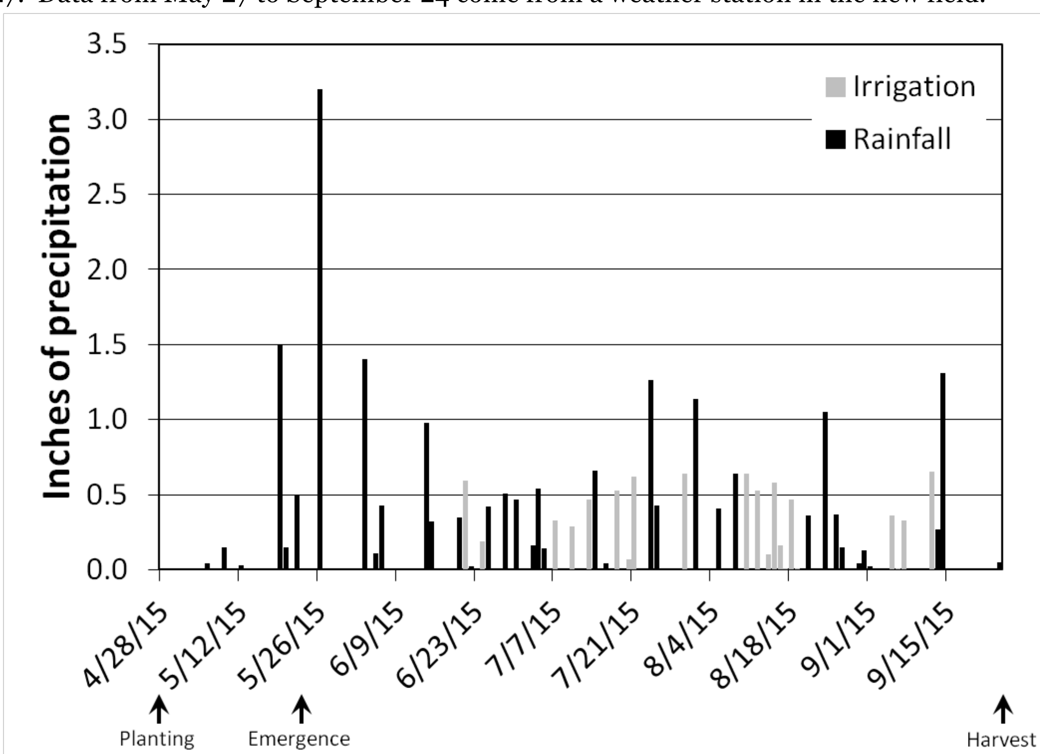

Table 3a. Effects of N application rate on soil water NO_3-N concentrations 4 feet below the soil surface of Russet Burbank potato fields in Park Rapids, MN, in 2015.

Nitrogen Treatments					Soil water NO_3-N (ppm)													
Field	Treatment	Nitrogen source[1]	Nitrogen application rate at emergence ($lbs \cdot ac^{-1}$)	Total nitrogen application rate ($lbs \cdot ac^{-1}$)	May 22	May 27	June 03	June 10	June 17	June 24	July 01	July 08	July 15	July 22	July 29	August 10	August 19	September 22
New	1	Control	0	110	15	23	44	85	70	40	50	54	48	48	49	55	43	31
	3	ESN	120	230	24	38	61	81	87	65	70	73	70	95	54	77	60	43
	6	ESN	240	350	29	47	82	98	104	97	87	83	70	72	67	73	70	57
Significance of application rate[2]					NS	*	*	NS	NS	++	++	NS	++	NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	17	21	--	--	34	26	--	17	--	--	--	--	--
Contrasts[3]				Linear	NS	*	**	NS	NS	*	*	NS	++	NS	NS	NS	++	NS
				Quadratic	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Old	1	Control	0	110	25	45	74	84	84	120	120	87	84	78	99	73	90	96
	3	ESN	120	230	28	39	70	97	78	120	125	122	137	75	127	113	118	114
	6	ESN	240	350	31	42	68	97	78	117	125	88	127	89	112	110	88	78
Significance of application rate[2]					NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	++	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	--	--	--	--	--	30	--	--	34	--	--
Contrasts[2]				Linear	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
				Quadratic	NS	NS	NS	NS	NS	NS	NS	++	*	NS	NS	++	NS	NS
Both	1	Control	0	110	21	36	64	84	79	72	85	84	79	65	77	79	74	68
	3	ESN	120	230	26	39	66	90	97	102	101	98	103	88	103	101	89	73
	6	ESN	240	350	30	52	76	97	91	103	102	86	93	79	85	88	77	65
Significance of application rate[2]					NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	--	--	--	--	--	--	--	--	--	--	--
Contrasts[2]				Linear	NS	++	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
				Quadratic	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
New	All treatments				23	42	66	88	89	71	67	69	62	74	57	67	60	44
Old	All treatments				28	42	71	93	90	119	123	109	129	80	113	106	101	98
Significance of field age[2]					NS	NS	++	NS	NS	**	**	*	**	NS	**	*	*	**
Significance of rate*field interaction[2]					NS	++	*	NS	NS	++	NS	NS	NS	NS	NS	NS	NS	NS

[1]ESN (Environmentally Smart Nitrogen; Agrium, Inc.): 44-0-0.

[2]NS: not significant. ++, *, **: significant at 10%, 5%, and 1%, respectively.

Table 3b. Effects of N source on soil water NO_3-N concentrations 4 feet below the soil surface of Russet Burbank potato fields in Park Rapids, MN, in 2015.

Nitrogen Treatments					Soil water NO_3-N (ppm)													
Field	Treatment	Nitrogen source[1]	Nitrogen application rate at emergence ($lbs \cdot ac^{-1}$)	Total nitrogen application rate ($lbs \cdot ac^{-1}$)	May 22	May 27	June 03	June 10	June 17	June 24	July 01	July 08	July 15	July 22	July 29	August 10	August 19	September 22
New	3	ESN	120	230	24	38	61	81	87	65	70	73	70	95	54	77	60	43
New	7	Urea	120	230	21	45	72	81	85	87	82	91	89	97	75	67	74	51
New	8	AS	120	230	32	36	73	94	98	78	73	116	128	107	77	68	68	57
New	9	SuperU	120	230	28	60	88	139	131	102	97	113	105	90	76	71	83	72
New	10	Urea + DCD	120	230	21	26	57	109	97	110	100	98	94		57	86	78	74
Significance of nitrogen source[2]					NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	--	--	--	--	--	--	--	--	--	--	--
Old	3	ESN	120	230	28	39	70	97	78	120	125	122	137	75	127	113	118	114
Old	7	Urea	120	230	18	35	44	58	70	99	113	85	107	89	86	90	92	81
Old	8	AS	120	230	22	26	46	79	90	111	93	80	85	80	49	86	82	69
Old	9	SuperU	120	230	13	32	55	95	89	111	112	109	123	78	112	110	99	99
Old	10	Urea + DCD	120	230	28	29	36	69	78	109	97	106	114		109	75	83	65
Significance of nitrogen source[2]					NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	--	--	--	--	--	--	--	--	--	--	--
Both	3	ESN	120	230	26	39	66	90	82	102	101	98	103	88	103	101	89	73
Both	7	Urea	120	230	20	41	60	73	80	91	92	88	95	93	80	78	83	64
Both	8	AS	120	230	27	31	59	90	93	89	83	92	96	91	60	76	74	62
Both	9	SuperU	120	230	22	44	71	117	110	106	105	111	114	83	94	91	91	85
Both	10	Urea + DCD	120	230	25	28	44	92	88	110	99	102	104	--	88	79	80	69
Significance of nitrogen source[2]					NS	NS	NS	++	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	36	22	--	--	--	--	--	--	--	--	--
New	All treatments				25	41	72	102	101	89	86	94	92	96	70	72	72	59
Old	All treatments				22	32	51	84	82	112	109	102	116	81	98	96	97	85
Significance of field age[2]					NS	NS	*	NS	*	++	*	NS	NS	NS	*	*	**	**
Significance of source*field interaction[2]					NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	++

[1]Ammonium sulfate: 21-0-0. ESN (Environmentally Smart Nitrogen; Agrium, Inc.): 44-0-0. Urea, SuperU (Koch Agronomic Services): 46-0-0.

[2]NS: not significant. ++, *, **: significant at 10%, 5%, and 1%, respectively.

Table 4a. Effects of N application rate on Russet Burbank tuber yield, grade, and size distribution in Park Rapids, MN, in 2015.

Field	Nitrogen Treatments: Treatment	Nitrogen source[1]	Nitrogen application rate at emergence (lbs·ac⁻¹)	Total nitrogen application rate (lbs·ac⁻¹)	Tuber yield: Unusable	0-3 oz	3-6 oz	6-10 oz	> 10 oz	Total yield	Usable yield	#1s > 3 oz.	#2s > 3 oz	Marketable yield	> 6 oz	> 10 oz
					cwt·ac⁻¹										% of usable yield	
New	1	Control	0	110	7	46	175	145 c	19 d	392 c	385 d	313 c	26	339 c	43 c	5 c
	2	ESN	80	190	7	52	207	213 ab	61 c	540 b	533 ab	455 ab	26	481 ab	51 b	11 b
	3	ESN	120	230	17	41	178	207 ab	94 b	537 b	520 bc	455 ab	25	479 ab	58 ab	18 a
	4	ESN	160	270	19	38	168	188 b	98 b	511 b	492 c	423 b	31	453 b	58 ab	20 a
	5	ESN	200	310	26	50	168	223 a	127 a	594 a	568 a	490 a	28	518 a	62 a	22 a
	6	ESN	240	350	5	46	153	190 ab	110 ab	506 b	500 bc	428 b	26	454 b	60 a	22 a
Significance of application rate[2]					NS	NS	NS	**	**	**	**	**	NS	**	**	**
Minimum significant difference (P < 0.1)					--	--	--	34	24	49	38	43	--	42	7	6
Contrasts[3]				Linear	NS	NS	++	*	**	**	**	**	NS	**	**	**
				Quadratic	NS	NS	NS	**	*	**	**	**	NS	**	++	NS
Old	1	Control	0	110	8	48	195 a	165 c	32 d	448 c	440 c	370 c	22	392 c	45 d	7 d
	2	ESN	80	190	4	55	209 a	212 a	72 c	552 ab	548 ab	464 ab	29	493 ab	52 c	13 c
	3	ESN	120	230	5	42	185 a	185 bc	101 bc	518 b	513 b	443 b	27	471 b	56 bc	20 b
	4	ESN	160	270	10	47	192 a	205 ab	137 a	591 a	581 a	508 a	26	534 a	59 ab	23 ab
	5	ESN	200	310	15	41	145 b	197 ab	115 ab	513 b	498 bc	426 b	31	457 b	63 a	23 ab
	6	ESN	240	350	10	46	143 b	188 b	145 a	531 ab	521 ab	442 b	33	475 b	64 a	28 a
Significance of application rate[2]					NS	NS	**	*	**	*	*	**	NS	**	**	**
Minimum significant difference (P < 0.1)					--	--	26	22	30	62	62	51	--	47	6	5
Contrasts[2]				Linear	NS	NS	**	NS	**	*	*	*	NS	**	**	**
				Quadratic	NS	NS	*	*	NS	*	*	**	NS	**	NS	NS
Both	1	Control	0	110	7	47	185 b	155 c	26 d	420 b	413 b	342 b	24	366 b	44 d	6 e
	2	ESN	80	190	6	53	208 a	213 a	67 c	546 a	541 a	460 a	28	487 a	52 c	12 d
	3	ESN	120	230	11	41	182 b	196 ab	98 b	528 a	516 a	449 a	26	475 a	57 b	19 c
	4	ESN	160	270	15	42	178 b	195 ab	115 ab	545 a	530 a	459 a	28	488 a	59 ab	21 bc
	5	ESN	200	310	20	46	157 c	210 a	121 a	553 a	533 a	458 a	30	487 a	62 a	23 ab
	6	ESN	240	350	8	46	148 c	189 b	128 a	519 a	511 a	435 a	30	465 a	62 a	25 a
Significance of application rate[2]					NS	NS	**	**	**	**	**	**	NS	**	**	**
Minimum significant difference (P < 0.1)					--	--	21	19	18	38	34	32	--	31	4	3
Contrasts[2]				Linear	NS	NS	**	**	**	**	**	**	NS	**	**	**
				Quadratic	NS	NS	**	**	*	**	**	**	NS	**	NS	NS
New	All treatments				14	46	175	194	85	513	500	427	27	454	55	17
Old	All treatments				9	46	177	191	99	523	514	440	28	468	56	19
Significance of field age[2]					NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	++
Significance of rate*field interaction[2]					NS	NS	NS	NS	NS	*	*	*	NS	*	NS	NS

[1]ESN (Environmentally Smart Nitrogen; Agrium, Inc.): 44-0-0.

[2]NS: not significant. ++, *, **: significant at 10%, 5%, and 1%, respectively.

Table 4b. Effects of N source on Russet Burbank tuber yield, grade, and size distribution in Park Rapids, MN, in 2015.

Field	Nitrogen Treatments				Tuber yield											
	Treatment	Nitrogen source[1]	Nitrogen application rate at emergence (lbs·ac^{-1})	Total nitrogen application rate (lbs·ac^{-1})	Unusable	0-3 oz	3-6 oz	6-10 oz	> 10 oz	Total yield	Usable yield	#1s > 3 oz.	#2s > 3 oz	Marketable yield	> 6 oz	> 10 oz
					cwt·ac^{-1}										% of usable yield	
New	3	ESN	120	230	17	41	178	207	94	537	520	455	25	479	58	18
New	7	Urea	120	230	9	57	170	210	91	538	528	437	35	471	57	17
New	8	AS	120	230	10	50	202	213	70	545	534	462	22	485	53	13
New	9	SuperU	120	230	15	45	188	206	82	536	521	451	25	476	55	16
New	10	Urea + DCD	120	230	16	56	184	207	73	535	519	444	20	464	54	14
Significance of nitrogen source[2]					NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	--	--	--	--	--	--	--	--	--
Old	3	ESN	120	230	5	42	185	185	101	518	513	443	27	471	56	20
Old	7	Urea	120	230	3	56	184	179	76	498	495	420	20	439	52	15
Old	8	AS	120	230	6	59	176	207	98	545	539	451	29	480	56	18
Old	9	SuperU	120	230	2	55	217	194	73	541	538	459	24	484	50	14
Old	10	Urea + DCD	120	230	5	49	178	206	72	509	504	424	31	455	55	14
Significance of nitrogen source[2]					NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	--	--	--	--	--	--	--	--	--
Both	3	ESN	120	230	11	41	182	196	98	528	516	449	26	475	57	19
Both	7	Urea	120	230	6	56	177	195	83	518	512	428	27	455	54	16
Both	8	AS	120	230	8	54	189	210	84	545	537	456	26	482	55	16
Both	9	SuperU	120	230	9	50	202	200	78	538	530	455	25	480	53	15
Both	10	Urea + DCD	120	230	11	53	181	206	72	524	513	435	25	460	54	14
Significance of nitrogen source[2]					NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	--	--	--	--	--	--	--	--	--
New	All treatments				14	50	184	208	83	538	524	449	26	474	55	16
Old	All treatments				4	52	189	193	84	522	518	440	26	466	53	16
Significance of field age[2]					**	NS	NS	++	NS	NS	NS	NS	NS	NS	NS	NS
Significance of source*field interaction[2]					NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]Ammonium sulfate: 21-0-0. ESN (Environmentally Smart Nitrogen; Agrium, Inc.): 44-0-0. Urea, SuperU (Koch Agronomic Services): 46-0-0.

[2]NS: not significant. ++, *, **: significant at 10%, 5%, and 1%, respectively.

Table 5a. Effects of N source on Russet Burbank tuber quality in Park Rapids, MN, in 2015.

(a)

Field	Nitrogen Treatments				Plant stand, July 10	Tuber Quality			
	Treatment	Nitrogen source[1]	Nitrogen application rate at emergence (lbs·ac^{-1})	Total nitrogen application rate (lbs·ac^{-1})		Specific Gravity	Hollow heart	Brown center	Other unusable
							% of usable yield		
New	1	Control	0	110	93	1.088 a	0.00	0.24	1.48
New	2	ESN	80	190	95	1.082 bc	0.00	0.00	0.82
New	3	ESN	120	230	93	1.085 ab	2.05	0.21	0.68
New	4	ESN	160	270	86	1.081 c	2.27	0.00	1.06
New	5	ESN	200	310	88	1.083 bc	3.20	0.00	0.51
New	6	ESN	240	350	83	1.083 bc	0.10	0.00	0.23
Significance of application rate[2]					NS	*	NS	NS	NS
Minimum significant difference (P < 0.1)					--	0.004	--	--	--
Contrasts[2]				Linear	*	*	NS	NS	++
				Quadratic	NS	++	NS	NS	NS
Old	1	Control	0	110	93	1.087	0.48	0.00	0.34
Old	2	ESN	80	190	90	1.088	0.00	0.16	0.26
Old	3	ESN	120	230	94	1.088	0.26	0.00	0.35
Old	4	ESN	160	270	89	1.086	1.40	0.00	0.07
Old	5	ESN	200	310	93	1.086	1.45	0.62	0.21
Old	6	ESN	240	350	92	1.084	0.84	0.00	0.09
Significance of application rate[2]					NS	NS	NS	NS	NS
Minimum significant difference (P < 0.1)					--	--	--	--	--
Contrasts[2]				Linear	NS	NS	NS	NS	NS
				Quadratic	NS	NS	NS	NS	NS
Both	1	Control	0	110	93	1.088 a	0.24	0.12	0.91
Both	2	ESN	80	190	93	1.085 ab	0.00	0.08	0.54
Both	3	ESN	120	230	93	1.086 ab	1.15	0.11	0.51
Both	4	ESN	160	270	88	1.083 b	1.90	0.00	0.64
Both	5	ESN	200	310	90	1.085 b	2.33	0.31	0.36
Both	6	ESN	240	350	88	1.084 b	0.47	0.00	0.16
Significance of application rate[2]					++	++	NS	NS	NS
Minimum significant difference (P < 0.1)					6	0.003	--	--	--
Contrasts[2]				Linear	*	**	NS	NS	*
				Quadratic	NS	NS	NS	NS	NS
New	All treatments				90	1.084	1.27	0.08	0.80
Old	All treatments				92	1.087	0.71	0.13	0.23
Significance of field age[2]					NS	**	NS	NS	**
Significance of rate*field interaction[2]					NS	NS	NS	NS	NS

[1]ESN (Environmentally Smart Nitrogen; Agrium, Inc.): 44-0-0.

[2]NS: not significant. ++, *, **: significant at 10%, 5%, and 1%, respectively.

Table 5b. Effects of N source on Russet Burbank tuber quality in Park Rapids, MN, in 2015.

(b)

Field	Nitrogen Treatments				Plant stand, July 10	Tuber Quality			
	Treatment	Nitrogen source[1]	Nitrogen application rate at emergence ($lbs \cdot ac^{-1}$)	Total nitrogen application rate ($lbs \cdot ac^{-1}$)		Specific Gravity	Hollow heart	Brown center	Other unusable
							% of usable yield		
New	3	ESN	120	230	93	1.085	2.05	0.21	0.68
New	7	Urea	120	230	95	1.087	1.14	0.00	0.38
New	8	AS	120	230	86	1.088	0.51	0.32	0.71
New	9	SuperU	120	230	89	1.085	0.54	0.37	1.34
New	10	Urea + DCD	120	230	96	1.084	0.95	0.59	1.09
Treatment significance					NS	NS	NS	NS	NS
Treatment MSD (P < 0.1)					--	--	--	--	--
Old	3	ESN	120	230	94	1.088	0.26	0.00	0.35
Old	7	Urea	120	230	92	1.087	0.00	0.00	0.33
Old	8	AS	120	230	93	1.087	0.77	0.00	0.21
Old	9	SuperU	120	230	89	1.088	0.00	0.13	0.30
Old	10	Urea + DCD	120	230	94	1.088	0.57	0.00	0.31
Treatment significance					NS	NS	NS	NS	NS
Treatment MSD (P < 0.1)					--	--	--	--	--
Both	3	ESN	120	230	93	1.086	1.15	0.11	0.51
Both	7	Urea	120	230	93	1.087	0.57	0.00	0.36
Both	8	AS	120	230	90	1.088	0.64	0.16	0.46
Both	9	SuperU	120	230	89	1.087	0.27	0.25	0.82
Both	10	Urea + DCD	120	230	95	1.086	0.79	0.34	0.76
Treatment significance, both fields combined					NS	NS	NS	NS	NS
Treatment MSD (P < 0.1)					--	--	--	--	--
New	All treatments				92	1.086	1.06	0.30	0.85
Old	All treatments				92	1.088	0.28	0.03	0.30
Field significance					NS	NS	++	++	*
Field * Treatment significance					NS	NS	NS	NS	NS

[1]Ammonium sulfate: 21-0-0. ESN (Environmentally Smart Nitrogen; Agrium, Inc.): 44-0-0. Urea, SuperU (Koch Agronomic Services): 46-0-0.
[2]NS: not significant. ++, *, **: significant at 10%, 5%, and 1%, respectively.