Effects of planting configuration and plant population density on the N response of Russet Burbank tuber yield and size

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Summary

The conventional hilled-row planting configuration for potato agriculture is non-uniform, with three to four times the space between rows as there is between plants within rows. This non-uniformity may both increase inter-plant competition for sunlight and soil N and decrease the efficiency with which the crop, as a whole, collects both. In turn, increased light and nutrient interception may be expected to increase crop yield and decrease nutrient losses. To increase planting uniformity, some growers have begun planting potatoes in beds with multiple, closely spaced rows between each pair of furrows. To evaluate whether this approach produces the anticipated benefits in terms of yield and soil N interception, we conducted an experiment with Russet Burbank potatoes near Staples, MN. A conventional hilled-row configuration was compared with a bed configuration, at population densities of 9,500 and 12,500 plants·ac^{-1}, fertilized at whole-season N rates of 80, 160, or 240 lbs·ac^{-1} N using a split-plot randomized complete block design with four blocks. Whole plots were defined by planting configuration and subplots by planting density and N rate. Averaged across densities and N rates, the bed plots had more Colorado potato beetle damage than the hilled-row plots. Hilled-row plots had higher marketable yields and more large tubers than bed plots. Averaged across planting configuration and N rate, high-density subplots had more undersized (< 3 oz.) tubers and U.S. No. 1 tubers, and fewer large (> 14 oz.) tubers and U.S. No. 2 tubers, than low-density subplots. In the hilled-row plots, the percentage of yield in tubers over 10 ounces was higher in low-density subplots. This effect of density was not significant in the bed plots. Bed plots had a higher prevalence of hollow heart, but also higher tuber specific gravity and dry matter content, than hilled-row plots. High-density subplots had a somewhat higher prevalence of scab than low-density subplots. Petiole NO_3^--N concentration was higher in hilled-row plots than bed plots, decreased with density, and increased with N rate. Soil water NO_3^--N concentration was also higher in hilled-row plots and increased with N rate. Overall, switching from the hilled-row configuration to the bed configuration was not supported by the results from this study. However, this experiment may have been compromised by poor Colorado potato beetle control early in the season, which affected bed plots substantially more than hilled-row plots. Poor beetle control is not typical of commercial fields, and this year's results may therefore be a poor indicator of how the bed configuration would perform in commercial practice.

Background

The conventional hilled-row planting configuration for potato agriculture has the benefit of providing rapid drainage to the soil around the tubers. However, because each row of plants has a furrow on either side of it, this configuration is not as space-efficient as a uniform configuration would be. Spacing between plants within rows is compact, increasing inter-plant competition, while spacing between rows is wide, reducing the efficiency with which the crop intercepts water, sunlight, and nutrients.

To correct these issues with the hilled-row configuration, growers have begun to plant potatoes in beds, in which multiple, more closely spaced rows of potatoes are planted between each pair of furrows. Plant spacing within each row is increased relative to the hilled-row configuration to compensate for the decreased between-row distance, making the planting arrangement relatively uniform. If greater uniformity improves the efficiency with which water, light, and nutrients are intercepted by the crop, the bed configuration can be expected to increase yield and decrease N losses due to NO_3^--N leaching compared to the hilled-row configuration. Because the distance to the nearest neighboring plant is maximized in a uniform distribution, competition among plants for resources, and the negative effects of high planting density on individual plants, are minimized. Based on this, we expect the responses of individual plants to differences in planting density to be weaker in a bed configuration than a hilled-row configuration.

To test these predictions, an experiment was conducted with Russet Burbank potatoes near Staples, MN. We compared a conventional hilled-row configuration with a bed configuration, at population densities of 9,500 and 12,500 plants·ac^{-1}, fertilized at whole-season N rates of 80, 160, or 240 lbs·ac^{-1} N. The specific objectives of this study were to determine whether the bed-planting configuration increased N uptake and tuber yield and decreased N requirements and N losses to leaching relative to the conventional hilled-row configuration, and whether these benefits were more pronounced at the higher density.

Methods

The study was conducted on 2018 at the Central Lakes College Agricultural and Energy Center near Staples, MN, under a linear irrigation system. The soil at the site is a Verndale sandy loam, and the previous crop was edible beans.

Initial soil samples to a depth of two feet (for NO_3^--N concentration) and six inches (for other characteristics) were collected on May 29. The two-foot samples were extracted with 2 N KCl and the extracts analyzed for NO_3^--N and NH_4^+-N using a Wescan Nitrogen Analyzer. The six-inch samples were sent to the University of Minnesota Research Analytical Laboratory (St. Paul, MN) to be analyzed for Bray P; NH_4OAc-extractable K, Ca, and Mg; $Ca(H_2PO_2)_2$ / Ba-extractable SO_4-S; hot-water-extractable B; DTPA-extractable Cu, Fe, Mn, and Zn; soil water pH; and LOI soil organic matter content. Results are presented in Table 1.

Preplant fertilizer was broadcast and incorporated over the entire plot area after soil sampling on May 29, two days before planting. The application was uniform over planting configuration and plant population treatments. Fertilizer application consisted of 500 lbs·ac^{-1} MOP (0-0-60), 200 lbs·ac^{-1} SulPoMag (0-0-22-18S-11Mg), 167 lbs·ac^{-1} diammonium phosphate (18-46-0), and 114 lbs·ac^{-1} ESN (Environmentally Smart Nitrogen, Agrium, Inc.; 44-0-0). In total, this provided 80 lbs·ac^{-1} N, 344 lbs·ac^{-1} K_2O, 77 lbs·ac^{-1} P_2O_5, 36 lbs·ac^{-1} S, and 22 lbs·ac^{-1} Mg.

The planting configuration, plant population density, and N rate treatments were arranged in a split-plot randomized complete block design with four blocks. Whole plots were defined by planting configuration (bed or hilled-row). Bed plots were 12 feet wide, with seven rows spaced 20.5 inches apart. Hilled-row plots were 18 feet wide, with six rows spaced 36 inches apart. Adjacent plots were separated by three feet.

Each whole plot was divided into six, 40-foot-ong subplots defined by planting density (9,500 or 12,500) and N application rate (80, 160 or 240 lbs·ac^{-1} N total). The within-row spacing of the seed pieces in bed plots was 32 inches at the low planting density and 24.5 inches at the high density. In hilled-row plots, within-row spacing was 18.5 inches at low density and 14 inches at high density. In the subplots receiving 160 or 240 lbs·ac^{-1} N, the additional N (beyond the 80 lbs·ac^{-1} N applied to the whole field) was applied as ESN by hand immediately after the whole-field fertilizer application. The planting and fertilizer treatments are summarized in Table 2.

Suction-tube lysimeters were installed both within and between the planting rows on June 1 (blocks 3 and 4) and 4 (blocks 1 and 2) to sample soil water at a depth of four feet. Lysimeters were flushed on June 6. The lysimeters between rows were installed several inches deeper than those within rows. In the hilled-row plots, this arrangement was enforced by the hilled-row topography, and the same vertical positioning was used in the bed plots to keep sampling depths consistent between the two treatments. Soil water samples were collected on 17 dates: June 13, 21, and 26; July 2, 9, 18, and 25; August 2, 9, 16, 20, and 30; September 6, 14, 19, and 26; and October 3. The samples have been tested for NO_3-N and NH_4-N concentration using a Wescan Nitrogen Analyzer.

Plant stand was measured on July 20 as the percentage of seed tubers in 40 feet of row that produced aboveground shoots. On the same day, because Colorado potato beetle control was poor, beetle damage was assessed in each plot. Damage was given a score of 0 to 5 based on the percentage of defoliation, where 0 indicated no damage, 1 indicated 1 – 20% defoliation, 2 indicated 21 – 40% defoliation, 3 indicated 41 – 60% defoliation, 4 indicated 61 – 80% defoliation, and 5 indicated greater than 80% defoliation. No plots received a score of five.

Petioles were collected from each plot on July 2 and 20 and August 2 to measure petiole NO_3^--N concentration. The petiole of the fourth leaf from the tip of the shoot was collected for each of 20 shoots per subplot. Petiole samples were analyzed for water-extractable NO_3^--N concentrations using a Wescan Nitrogen Analyzer.

Tubers were harvested from the same area used for vine samples on October 4, 126 days after planting. Tubers were sorted and graded on October 30. A 25-tuber sample was taken for quality measurements, including the prevalence of hollow heart, brown center, and scab and tuber specific gravity and dry matter content.

Data were analyzed using the MIXED procedure with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.). Stand, beetle damage, yield, and tuber quality variables were modeled as functions of planting configuration, population density, N application rate, and their interaction, with block as a fixed effect and block*configuration as random effect.

Petiole NO_3^--N concentration was modeled in a repeated-measures analysis as a function of sampling date, planting configuration, population density, N rate, and their interactions, with block and block*configuration as fixed effects (the model could not execute with block*configuration as a random effect), sampling date as the repeated-measures variable, and plot as the subject variable. A compound symmetrical correlation matrix structure was used.

Ideally, soil water NO_3^--N concentration could have been analyzed in the same manner as petiole NO_3^--N concentration, but there were too many gaps in the data for the model to execute. Instead, the data for each sampling date were analyzed separately, as functions of configuration, N rate, lysimeter placement (within or between rows), their interactions, and block. The data for the last three sample dates (September 19 and 26 and October 3) were too sparse to permit analysis.

In all models, denominator degrees of freedom were estimated by the Kenward-Rogers approximation. Pairwise comparisons between treatments were made using the DIFF option in an LSMEANS statement. Comparisons were made when a fixed effect in the model was significant at $\alpha = 0.10$, and differences were considered significant when the P-value of the comparison was less than 0.10.

Results and discussion

Plant stand and Colorado potato beetle damage

Results for plant stand and the Colorado potato beetle damage assessment, both measured on July 20 (50 days after planting) are presented in Table 3. Stand was significantly higher in the bed plots (averaged across densities and N rates) and the low-density subplots (averaged across configurations and N rates) than in the hilled-row plots and high-density plots, respectively.

Stand was highest at and N rate of 160 $lbs \cdot ac^{-1}$ N in the bed plots, but lowest at this N rate in the hilled-row plots, resulting in a significant effect of the interaction between planting configuration and N rate. This effect is difficult to explain and may not be meaningful.

Calculated stand sometimes exceeded 100%, especially in the bed plots configuration at low density. This is due, at least in part, to the greater impact of noise in the count data when few plants are expected to occur in 40 feet of sampled row. Just 15 plants were expected in the sampled area in the bed configuration at low density.

Beetle damage was more severe in the bed plots than the hilled-row plots. The effect of the interaction among planting configuration, planting density, and N rate was also significant, but this effect is difficult to interpret. Because the main effect of planting configuration was quite pronounced, the presence of the significant three-way interaction effect does not invalidate it. It is not clear why the Colorado potato beetle damage was worse in the bed plots, nor whether this result was due to greater beetle activity in the bed plots, poorer shoot growth in those plots, or a combination of the two.

Tuber size and yield at harvest

Results for tuber yield and size at harvest are presented in Table 4. Total tuber yield per acre was higher in hilled-row plots than bed plots and higher in high-density subplots than low-density subplots. The effect of the interaction among planting configuration, planting density, and N rate, was marginally significant. This effect is difficult to interpret. Marketable yield (yield excluding undersized tubers) generally paralleled total yield, but the effect of plot configuration on marketable yield was only marginally significant, while the effect of planting density was not statistically significant. Planting density affected total yield more than marketable yield because much of the difference in total yield between high- and low-density subplots was due to high yields of undersized tubers in high-density subplots.

Yields of both U.S. No. 1 and U.S. No. 2 grade tubers were higher in the hilled-row plots than the bed plots, but the difference was only significant for U.S. No. 2 tubers. High-density subplots (averaged across planting configuration and N rate) had higher yields of U.S. No. 1 tubers and lower yields of U.S. No. 2 tubers than low-density subplots, indicating that high planting density confers benefits in terms of potato grade as well as yield. The benefit of density for U.S. No. 1 potato yield were more pronounced in bed plots than hilled-row plots. The effect of N rate on potato grade differed between hilled-row plots and bed plots. In hilled-row plots, the yield of U.S. No. 1 potatoes decreased, while the yield of U.S. No. 2 potatoes increased, as the application rate of N increased. In bed plots, the yield of U.S. No. 1 tubers was numerically higher at 240 $lbs \cdot ac^{-1}$ N than at the lower rates, while the yield of U.S. No. 2 tubers was numerically higher at 160 $lbs \cdot ac^{-1}$ N than at 80 or 240 $lbs \cdot ac^{-1}$ N, though none of these differences were statistically significant.

Tuber quality

Tuber quality results are presented in Table 5. Averaged across density and N rate, bed plots had a significantly higher prevalence of hollow heart and higher tuber specific gravity than hilled-row plots, with similar but less significant results for tuber dry matter content. Averaged across configuration and N rate, high-density subplots tended to have a higher prevalence of scab than low-density subplots.

Petiole NO_3^--N concentrations

Results for petiole NO_3^--N concentrations are presented in Table 6. Averaged across treatments, petiole NO_3^--N decreased significantly from each sample date to the next. For the most part, the slope of this decline was unrelated to treatment factors, the exception being planting configuration. Season-average petiole NO_3^--N concentration was higher in hilled-row plots than bed plots (averaged across planting densities and N rates), and this difference became smaller from each sample date to the next, no longer being significant by the third date (August 3).

Averaged across planting configurations and N rates, plants in low-density subplots had a slightly higher season-average petiole NO_3^--N concentration than high-density subplots. This suggests that lower planting density decreases inter-plant competition for nutrients and increases the ability of individual plants to take up soil N.

Averaged across planting configurations and densities, subplots receiving 240 $lbs \cdot ac^{-1}$ N total had a higher season-average petiole NO_3^--N concentration than subplots receiving 160 $lbs \cdot ac^{-1}$ N, which had a higher concentration than subplots receiving 80 $lbs \cdot ac^{-1}$ N. This result indicates that, as expected, plant tissue N concentrations are limited by soil N availability.

No other interactions among planting configuration, planting density, N rate, and date were significantly related to petiole NO_3^--N concentration.

Soil water NO_3^--N concentration

Results for soil water NO_3^--N concentration are presented in Table 7. Planting configuration was a significant predictor of soil water NO_3^--N concentration on six of the 14 sample dates presented. In each case, the concentration was higher in the hilled-row plots than the bed plots.

The application rate of N was also significantly related to soil water NO_3^--N concentration on six sample dates. On July 18 and 25, the subplots receiving 160 or 240 $lbs \cdot ac^{-1}$ N had higher concentrations than those receiving 80 $lbs \cdot ac^{-1}$ N. On all later dates on which the effect of N rate was significant, the subplots receiving 240 $lbs \cdot ac^{-1}$ N had a higher mean soil water NO_3^--N concentration than those receiving 80 or 160 $lbs \cdot ac^{-1}$ N.

Lysimeter placement within the plot was only significantly related to soil water NO_3^--N concentration on three dates. On June 26 and July 2, the lysimeters placed within rows had higher concentrations than those placed between rows. The opposite was true on August 30.

The effect of N rate on soil water NO_3^--N concentration differed between the two planting configurations on three dates (July 18 and August 9 and 16). In each case, the N response was more pronounced in the hilled row plots (with higher N rates producing higher soil water concentrations) than in the bed plots.

The interaction between planting configuration and lysimeter placement was significant on three dates. On July 9, lysimeters placed between rows in bed plots had a lower mean concentration than those placed within rows or those in hilled-row plots. The results were similar on July 25, except that the difference between lysimeters within and between rows in bed plots was not significant. On August 20, the results were similar to those of July 25 except that the lysimeters within rows in the hilled-row plots had a similar (low) mean soil water NO_3^--N concentration to those placed between rows in bed plots.

The response of soil water NO_3^--N concentration to N rate depended on lysimeter placement on July 18 and August 9. In each case, the concentrations found in lysimeters placed between rows were positively related to the application rate of N while the concentrations found in lysimeters placed within rows peaked at an N rate of 160 $lbs \cdot ac^{-1}$ N total.

On August 9 and 20, the effect of the interaction among planting configuration, N rate, and lysimeter placement was significant. In each of these cases, soil water NO_3^--N concentration varied more with lysimeter placement and N rate in the hilled-row plots than the bed plots.

Conclusions

In terms of yield, the conventional hilled-row planting configuration performed better than the bed configuration in this study. However, the effects of N rate on tuber yield and size in this study were surprisingly limited, since Russet Burbank yield and tuber size are typically limited primarily by N in irrigated systems. It is possible that the late planting date (May 31) and resulting short growing season greatly diminished the potential for N rate to influence crop performance.

In addition to lower petiole NO_3^--N concentrations, the bed plots had lower soil water NO_3^--N concentrations than the hilled-row plots on several sampling dates. Thus, the differences in petiole NO_3^--N concentration are not explained by greater NO_3^--N leaching from the bed plots. Vines were not noticeably larger in the bed plots, making a dilution effect on petiole NO_3^--N an unlikely explanation. It is possible that the bed plots lost more N than the hilled-row plots through pathways other than NO_3^--N leaching, that plant tissue N in the bed plots is more likely to occur in forms other than petiole NO_3^--N than tissue N in hilled-row plots, or much of the N taken up by plants in bed plots was lost to Colorado potato beetles, which did significantly more damage to plants in bed plots than hilled-row plots. These mechanisms may also explain the lower yields observed in bed plots.

Individual plants in the bed configuration were expected to be less sensitive to planting density than those in the hilled-row configuration. If this had occurred, whole-field variables that are positively related to density, like yield per acre, would have increased more with density in beds than hilled rows. Whole-field variables that are negatively related to planting density, like soil water NO_3^--N concentration, would have decreased more with density in beds than hilled rows. Variables that are determined mostly by the access of individual plants to light, water, or nutrients, like tuber size and grade and petiole NO_3^--N concentration, would have been less responsive to density in beds. Some of our results were consistent with these expectations. Marketable yield numerically increased with planting density in beds but did not respond to density in hilled rows. The percentage of yield in tubers over 10 ounces decreased significantly less at higher density in beds than hilled rows. Petiole NO_3^--N concentration numerically decreased less in beds than hilled rows at high density. However, tuber grade, in terms of both U.S. No. 1 yield and U.S. No. 2 yield, was more sensitive to density in the beds than hilled rows, contrary to expectation.

Overall, results for 2018 do not support changing planting configuration and density from the conventional hilled-row configuration. However, these results may be an effect of the poor Colorado potato beetle control in this field in the first half of the season. Beetle damage may have depressed yield, tuber size, and petiole NO_3^--N concentration, and the bed plots suffered substantially more damage, overall, than the hilled-row plots. Better beetle control (combined with a more typical planting date) in future research may reveal an advantage to bed planting not evident in this study.

Table 1. Initial soil characteristics of the study site in Staples, MN, in 2018.

0 - 2 feet	0 - 6 inches											
NO_3-N	Bray P	K	SO_4-S	Ca	Mg	Fe	Mn	Zn	Cu	B	Organic matter	pH
mg·kg^{-1} soil												
8.2	31	110	8	1320	133	28	22	3.3	0.63	0.18	1.6	6.5

Table 2. Planting configuration, population density, and N application rate treatments applied to Russet Burbank potatoes near Staples, MN, in 2018. Whole plots were defined by planting configuration, while subplots were defined by planting density and N rate.

Planting configuration	Planting density (seed pieces·ac^{-1})	Seed spacing within row (inches)	Total N application rate (lbs·ac^{-1})[1]
Bed (row spacing 20.5 inches)	9500	32	80
			160
			240
	12500	24.5	80
			160
			240
Hilled row (row spacing 36.0 inches)	9500	18.5	80
			160
			240
	12500	14	80
			160
			240

[1]30 lbs·ac^{-1} N was applied as DAP (18-46-0), with the rest as ESN (Environmentally Smart Nitrogen, Agrium, Inc.; 44-0-0), all at planting.

Table 3. Effects of planting configuration, planting density, and N application rate on percent stand and severity of Colorado potato beetle damage on July 20 to Russet Burbank potato plants grown near Staples, MN, in 2018. The beetle damage score ranged from 0 (no damage) to 5 (over 80% defoliation).

Planting configuration	Planting density (seed pieces·ac^{-1})	Total N applied[1] (lbs·ac^{-1})	Stand (%)	Beetle damage score
Bed	9500	80	99	1.83 abc
		160	109	1.56 abcd
		240	101	2.16 ab
	12500	80	97	1.93 abc
		160	99	2.47 a
		240	94	0.92 bcde
Hilled row	9500	80	96	0.73 cde
		160	94	0.25 ef
		240	93	0.06 f
	12500	80	92	0.56 def
		160	89	0.25 ef
		240	94	1.00 bcde
Significance of model effects (P-values)	Planting configuration		**0.0276**	**0.0205**
	Planting density		**0.0095**	0.5303
	N rate		0.3607	0.5463
	Configuration*density		0.2484	0.3122
	Configuration*N rate		**0.0416**	0.4890
	Density*N rate		0.3450	0.8128
	Configuration*density*N rate		0.3878	**0.0356**

Table 4. Effects of planting configuration, planting density, and N application rate on tuber yield, size, and grade of Russet Burbank potatoes grown near Staples, MN, in 2018.

Planting configuration	Planting density (seed pieces·ac^{-1})	Total N applied[1] (lbs·ac^{-1})	Tuber yield										
			0-3 oz	3-6 oz	6-10 oz	10-14 oz	> 14 oz	Total yield	#1s > 3 oz.	#2s > 3 oz	Marketable yield	> 6 oz	> 10 oz
			cwt·ac^{-1}									%	
Bed	9500	80	44	88	100	18	24	275 e	142	89	231 d	51	15
		160	58	81	99	51	83	372 bcd	167	147	313 bc	61	35
		240	53	99	76	51	48	327 de	157	117	274 cd	53	29
	12500	80	58	110	123	55	20	365 bcd	245	63	308 bc	53	19
		160	67	109	102	45	28	351 cd	218	66	284 cd	47	18
		240	53	129	128	60	32	402 abc	309	40	349 ab	55	23
Hilled row	9500	80	53	82	116	86	50	387 abc	219	114	334 abc	65	35
		160	38	56	92	105	102	391 abc	200	154	354 ab	76	52
		240	43	71	77	98	119	408 ab	210	156	366 ab	71	52
	12500	80	52	100	143	85	49	430 a	297	80	378 a	65	31
		160	59	111	135	67	46	417 ab	263	95	358 ab	59	27
		240	70	105	108	70	33	386 abc	213	102	316 bc	54	26
Significance of model effects (P-values)	Planting configuration		0.6910	*0.0607*	0.5657	**0.0320**	0.1267	**0.0436**	0.3579	**0.0206**	*0.0797*	0.1026	**0.0332**
	Planting density		*0.0751*	**0.0003**	**<0.0001**	0.5690	**0.0016**	**0.0203**	**<0.0001**	**<0.0001**	0.1545	**0.0313**	**0.0006**
	N rate		0.8761	0.4837	**0.0269**	0.6526	*0.0816*	0.4419	0.7459	0.1769	0.6204	0.7661	*0.0827*
	Configuration*density		0.5099	0.5744	0.5608	**0.0319**	0.2977	0.2154	*0.0873*	0.6089	0.1448	0.2507	*0.0718*
	Configuration*N rate		0.4448	0.6295	0.2034	0.5773	0.7973	0.1906	*0.0752*	0.5128	0.2486	0.8265	0.9020
	Density*N rate		0.8273	0.5283	0.4632	0.1212	*0.0925*	0.1427	0.6714	0.3734	0.1066	0.1332	**0.0252**
	Configuration*density*N rate		0.3814	0.6934	0.1888	0.9882	0.2997	*0.0850*	*0.0971*	0.8407	*0.0754*	0.4409	0.6991

[1]30 lbs·ac^{-1} N was applied as DAP (18-46-0) with the rest as ESN (Environmentally Smart Nitrogen, Agrium, Inc.; 44-0-0) at planting.

Table 5. Effects of planting configuration, planting density, and N application rate on tuber quality (prevalence of hollow heart / brown center and scab; tuber specific gravity; and tuber dry matter content) of Russet Burbank tubers grown near Staples, MN, in 2018.

Planting configuration	Planting density (seed pieces·ac^{-1})	Total N applied[1] (lbs·ac^{-1})	Hollow heart / brown center	Scab	Tuber specific gravity	Tuber dry matter content (%)
			% of tubers			
Bed	9500	80	21	5	1.0882	24.9
		160	6	0	1.0879	24.9
		240	15	4	1.0919	24.5
	12500	80	15	8	1.0914	24.0
		160	16	13	1.0935	25.2
		240	12	8	1.0885	24.9
Hilled row	9500	80	5	0	1.0889	23.7
		160	4	8	1.0825	21.9
		240	5	4	1.0830	22.6
	12500	80	16	4	1.0897	24.0
		160	7	8	1.0877	23.6
		240	2	4	1.0835	22.2
Significance of model effects (P-values)	Planting configuration		**0.0080**	0.6805	**0.0070**	*0.0607*
	Planting density		0.5110	*0.0821*	0.1956	0.5422
	N rate		0.1574	0.5446	0.3241	0.4036
	Configuration*density		0.5445	0.2532	0.9006	0.3869
	Configuration*N rate		0.8342	0.5356	0.1946	0.1038
	Density*N rate		0.3450	0.6700	0.1927	0.2854
	Configuration*density*N rate		0.1885	0.4392	0.5766	0.4126

[1]30 lbs·ac^{-1} N was applied as DAP (18-46-0), with the rest as ESN (Environmentally Smart Nitrogen, Agrium, Inc.; 44-0-0), all at planting.

Table 6. Effects of planting configuration, planting density, N application rate, and sampling date on petiole NO_3^--N concentration in Russet Burbank potato plants grown near Staples, MN, in 2018.

Planting configuration	**Planting density (seed pieces·ac^{-1})**	**Total N applied[1] (lbs·ac^{-1})**	**Petiole NO_3^--N (mg·kg^{-1})**		
			July 2	**July 20**	**August 3**
Bed	9500	80	23279	7455	1983
		160	24597	12368	6012
		240	25882	11524	4312
	12500	80	22884	8844	4873
		160	24993	8383	1085
		240	26599	13325	5419
Hilled row	9500	80	28296	12400	2783
		160	28050	12746	4904
		240	29033	17203	6963
	12500	80	25907	9621	1860
		160	28534	11435	3630
		240	29108	14771	5956
Significance of model effects (P-values	Date		**<0.0001**		
	Configuration		**<0.0001**		
	Density		*0.0969*		
	N rate		**<0.0001**		
	Configuration*density		0.1626		
	Configuration*N rate		0.7230		
	Density*N rate		0.1815		
	Configuration*density*N rate		**0.0200**		
	Configuration*date		**0.0097**		
	Density*date		0.5996		
	N rate*date		0.4270		
	Configuration*density*date		0.8220		
	Configuration*N rate*date		0.5047		
	Density*N rate*date		0.2230		
	Configuration*density*N rate*date		0.7047		

Table 7. Effects of planting configuration, N application rate, and lysimeter placement on soil water NO_3^--N concentration under Russet Burbank potatoes grown near Staples, MN, in 2018. Gaps in the data prevented a repeated-measures analysis, and results for each sampling date were therefore analyzed separately.

Planting configuration	Total N applied[1]	Lysimeter placement	Soil water NO_3^--N (ppm)													
			6/13	**6/21**	**6/26**	**7/2**	**7/9**	**7/18**	**7/25**	**8/2**	**8/9**	**8/16**	**8/20**	**8/30**	**9/6**	**9/14**
Bed	80	Between rows	10	22	42	35	64	60	70	52	63 d	71	65 c	54	70	56
		In row	11	30	39	60	97	68	77	85	82 d	62	76 bc	55	34	51
	160	Between rows	9	28	34	50	62	82	76	47	64 d	52	68 c	77	50	53
		In row	11	33	38	82	103	108	110	62	72 d	50	72 c	41	5	35
	240	Between rows	10	29	38	55	69	78	87	92	89 cd	74	71 c	84	83	74
		In row	10	41	49	66	113	73	94	125	94 cd	75	155 ab	90	197	80
Hilled row	80	Between rows	18	39	48	59	73	78	74	85	115 cd	69	88 bc	99	81	86
		In row	14	21	56	73	91	71	80	65	75 d	77	39 c	18	28	52
	160	Between rows	22	43	49	67	117	78	106	75	141 bc	124	99 bc	127	124	95
		In row	10	31	63	69	94	99	108	137	199 a	132	109 bc	91	70	74
	240	Between rows	7	14	41	73	120	122	139	172	185 ab	145	210 a	148	184	113
		In row	8	26	73	96	119	94	97	118	75 d	127	91 bc	47	109	153
Configuration			0.1667	0.8479	*0.0584*	0.2225	0.2821	0.3842	*0.0527*	*0.0527*	**0.0008**	**0.0032**	0.2184	0.3833	0.3697	**0.0146**
N rate			0.2747	0.6247	0.8504	0.3210	0.1796	**0.0158**	**0.0065**	**0.0154**	0.1045	0.1420	**0.0310**	0.4811	**0.0273**	*0.0663*
Placement			0.3742	0.8096	*0.0922*	*0.0517*	0.1166	0.6869	0.7383	0.4600	0.4817	0.9021	0.5724	*0.0733*	0.3722	0.6857
Configuration*N rate			0.2751	0.2882	0.8977	0.5290	0.5110	*0.0996*	0.3916	0.4647	*0.0560*	*0.0607*	0.5153	0.6260	0.5522	0.5207
Configuration*placement			0.1848	0.1021	0.2441	0.5680	*0.0846*	0.2262	*0.0725*	0.3145	0.1599	0.9351	**0.0202**	0.1668	0.2222	0.9826
N rate*Placement			0.6863	0.1869	0.3870	0.9807	0.8417	*0.0592*	0.1603	0.4862	*0.0819*	0.9545	0.7614	0.9711	0.5049	0.4083
Configuration*N rate*placement			0.4561	0.4164	0.9007	0.6470	0.6425	0.8673	0.4218	0.2390	*0.0703*	0.8959	*0.0558*	0.5134	0.3225	0.6921

[1] 30 lbs·ac^{-1} N was applied as DAP (18-46-0), with the rest as ESN (Environmentally Smart Nitrogen, Agrium, Inc.; 44-0-0), all at planting.