Nitrogen Requirements for Potatoes Grown in a Bed-planting Configuration

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Summary

Planting potatoes in a bed configuration, with several rows planted between each pair of furrows, may be expected to confer advantages over the conventional hilled-row configuration. In particular, the more uniform spacing of the bed configuration may allow the crop to more efficiently intercept sunlight, nutrients, and water, which may result in improved yields and reduced nutrient losses. Our research on this approach to date indicates that the bed configuration may be superior to the hilled-row configuration for whole seed tuber production, but perhaps not for processing tuber production. To determine whether these findings on are robust, we planted Russet Burbank potatoes in two configurations (bed and hilled-row) at two densities (13,000 and 34,000 seeds·ac^{-1}), applying N at three rates (150, 200, and 250 lbs·ac^{-1} N). The study had a split-plot randomized complete block design with four replicates, whole plots defined by planting configuration, and subplots defined by planting density and N rate. We analyzed the effects of these treatments on tuber yield, grade, size, and quality. Potatoes grown in the bed configuration produced somewhat more undersized tubers (suitable as whole seed) and fewer marketable tubers, with less marketable yield in tubers over six ounces, than those grown in the hilled-row configuration. Planting density had a stronger effect, with potatoes planted at high density producing substantially more undersized tubers, fewer marketable tubers for processing, and less of their marketable yield in tubers over six or ten ounces than potatoes planted at low density. N rate had little effect on tuber yield, but potatoes grown at the lowest N rate (150 lbs·ac^{-1} N) had less of their yield in tubers over six ounces than those receiving N at higher rates. Both tuber specific gravity and tuber dry matter content were higher in the bed configuration than the hilled-row configuration, higher at high density than low density, and lower in the lowest-N treatments than in treatments receiving higher rates of N. However, the results for tuber dry matter are difficult to interpret due to a significant effect of the interaction among planting configuration, density, and N rate. Petiole NO_3^--N concentrations were higher in hilled-row plots than bed plots, were higher at low density than high density, and increased with the application rate of N. Soil water NO_3^--N concentrations were higher in low-density subplots than high-density subplots. Vine and tuber N concentrations, as well as vine and total (vine plus tuber) N uptake, were lower in subplots receiving 150 lbs·ac^{-1} N than in those receiving the two higher rates. Vine N concentration and vine, tuber, and total N uptake were higher in hilled-row plots than bed plots. End-of-season soil NO_3—N concentration was not related to treatment. Based on results over two years, planting at high density in a bed configuration is superior to planting at low density or in a hilled-row configuration for whole seed tuber production. Conversely, the hilled-row configuration at low density is superior for processing-tuber production. A benefit of bed planting for lower soil water nitrate concentrations below the root zone was found in 2018, but not in 2019. Overall, bed configuration did not confer the benefits in terms of N uptake, yield, and tuber size for processing potatoes or reduced nitrate leachig originally hoped for.

Background

Potatoes for French fry production are grown in hilled rows, which provide furrows for drainage to prevent tubers from being exposed to excessive moisture. However, this may not be the optimal configuration in terms of tuber yield or quality, weed suppression, or the ability of the crop to intercept supplied nutrients, reducing nutrient losses. One planting configuration that has received recent attention is a bed configuration, in which several rows of potatoes are planted between widely-spaced furrows.

Because spacing is more uniform in the bed configuration than the hilled-row configuration, within-row spacing being much more similar to between-row spacing, it is plausible that potatoes grown in a bed configuration would both achieve canopy closure and spread roots throughout the available space (achieve canopy closure underground, so to speak) earlier in the season than those grown in a hilled-row configuration. This, in turn, may be expected to improve the interception of light, nutrients, and water, potentially improving tuber yields while decreasing nutrient losses.

Over the 2017 and 2018 field seasons, we evaluated the bed configuration for both seed and processing tuber production. In 2017, we focused on seed production and found that the bed configuration yielded more whole seed per acre than the hilled-row configuration, though the difference in total (whole plus cut) seed production was not statistically significant. In 2018, we tested whether the bed configuration was suitable for producing processing tubers and found that it had lower marketable yield and less yield in tubers over ten ounces than the hilled-row configuration while generating higher rates of hollow heart and brown center. These results may be due, at least in part, to poor Colorado potato beetle control, which had a stronger impact on the bed plots and would not be likely to occur in commercial production. Overall, the results of our research indicate that the bed configuration may be superior to the hilled-row configuration for producing whole seed, while it is not clear that it offers any benefits for processing tuber production.

In 2019, to determine whether our findings on the suitability of the bed configuration for whole seed production were robust, we evaluated the effects on Russet Burbank potatoes of planting configuration (bed versus hilled-row) at two densities ($13{,}000\cdot ac^{-1}$, suitable for processing, and $34{,}000\cdot ac^{-1}$, suitable for seed) and three N rates (150, 200, and 250 $lbs\cdot ac^{-1}$ N in total) in a truncated growing season suitable for seed production (85 days from planting to vine kill). A split-plot randomized complete block design was used, with four replicates, whole plots defined by planting configuration, and subplots defined by planting density and N rate.

Methods

Study design

The study was conducted in 2019 at the Central Lakes College Agricultural and Energy Center near Staples, MN, under a pivot irrigation system. The soil at the site is a Verndale sandy loam, and the previous crop was edible beans. Twelve treatments were applied in a split-plot randomized complete block design with four replicates. Whole plots were defined by planting configuration (bed or hilled-row). Plots were 12 feet wide. Bed plots had seven rows spaced 20.5 inches apart, while hilled-row plots had four rows spaced 36 inches apart. Adjacent plots were separated by three feet. Forty-foot-long subplots were defined by two levels of planting density and three levels of N application rate.

Planting and fertilizer application

Whole “B” Russet Burbank seed pieces were planted in each subplot on June 11, at a density of 13,000 pieces/ac (a within-row spacing of 24 inches in bed plots and 14 inches in hilled-row plots, typical of processing-tuber production) or 34,000 pieces/ac (a within-row of spacing 9 inches in bed plots and 5 inches in hilled-row plots, typical of seed-tuber production). Hilling was carried out immediately after planting.

N was applied to each subplot at 150, 200, or 250 $lbs\cdot ac^{-1}$ in total. All treatments received 141 $lbs\cdot ac^{-1}$ sulfate of potash (0-0-50-17S) at planting, providing 70 $lbs\cdot ac^{-1}$ K and 24 $lbs\cdot ac^{-1}$ SO_4-S, and 150 $lbs\cdot ac^{-1}$ N as 28% UAN throughout the season. In addition, the lowest-N treatment received 161 $lbs\cdot ac^{-1}$ TSP (0-45-0-15Ca) before planting, providing 72 $lbs\cdot ac^{-1}$ P_2O_5

and 24 lbs·ac^{-1} Ca). The two higher-N treatments received as DAP applied at 161 lbs·ac^{-1} DAP (18-46-0, providing 29 lbs·ac^{-1} N and 74 lbs·ac^{-1} P_2O_5) before planting plus 48 or 161 lbs·ac^{-1} Environmentally Smart Nitrogen (ESN, 44-0-0, providing 21 or 71 lbs·ac^{-1} N).

Petiole NO_3^--N

Petioles were collected from each subplot on July 12 and 25 and August 14. The petiole of the fourth mature leaf from the shoot tip was collected from 20 shoot per subplot. The samples were dried at 140°F until their weight was stable, ground, and analyzed for NO_3^--N concentrations using a Wescan Nitrogen Analyzer.

Soil water NO_3^--N

To sample soil water at a depth of four feet, a suction-tube lysimeter was installed in each subplot on June 17 for blocks 2 – 4 and June 18 for block 1. Each lysimeter was installed near the center of the subplot and two rows in from the long edge. All lysimeters were flushed and tested on June 18. Water samples were collected on June 24, July 5, 10, 18, and 24, August 1, 9, 16, 21, and 28, and September 5 and 20. Soil water NO_3^--N concentrations were determined using a Wescan Nitrogen Analyzer.

Vine N uptake

Vine samples were collected from 15 feet of row in each subplot on September 3. In bed subplots, 3.2 feet of an edge row and 11.8 feet of the adjacent interior row were sampled. In hilled-row subplots, all 15 feet were taken from an interior row. Different sampling strategies were used because, in a field planted with a bed configuration, the plants at the edges of the beds experience a slightly different environment than those in the middles of the beds, even far from the field borders. This is not the case in the hilled-row configuration, with a single row of plants in each hill. Vine samples were weighed. A subsample was taken from each sample, weighed, dried at 140°F until its weight had stabilized, and re-weighed. The dried tissue was analyzed for total N concentration with an Elementar CNS Element Analyzer in order to estimate above-ground N uptake. The remaining vines in the field were killed with desiccant spray after the samples were taken.

Tuber harvest

Tubers were harvested by hand from the same areas used for vine sampling on September 20, 95 days after planting. The tubers were sorted and graded on October 8. Twenty-five-tuber subsamples were collected for each plot, stored at 48°F, and assessed for hollow heart, brown center, and scab, and their specific gravity and dry matter content were determined. A separate sample was dried and analyzed for total N concentration with an Elementar CNS Element Analyzer in order to estimate tuber N uptake.

End-of-season soil NO_3^--N concentration

Soil samples to a depth of one foot were collected from each plot on September 20, dried at 95°F until their weight was stable, ground, and analyzed for NO_3^--N concentration using a Wescan Nitrogen Analyzer.

Data analysis

Data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the GLIMMIX procedure. Most variables were modeled as functions of planting configuration, population density, N application rate, and their interactions, 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.

In all models, a normal data distribution was assumed and the 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

Tuber yield, size, and grade

The results for tuber yield, size, and grade are presented in Table 2. Total tuber yield was not significantly related to treatment. Between 40% and 86% of total yield was represented by tubers under four ounces, depending on the treatment. Marketable yields were higher in subplots with a hilled-row planting configuration than a bed configuration, and substantially higher in low-density subplots than in high-density subplots. Given the lack of treatment effects on total yield, it is not surprising that the results for yield of undersized tubers were the inverse of those for marketable yield, with more undersized yield in the bed configuration and at high density than in the hilled-row configuration or at low density.

The vast majority of tubers of marketable size were U.S. No. 1, and the statistical results for this grade were essentially the same as for marketable yield as a whole. On average, U.S. No. 2 tubers accounted for less than 1% of yield, and statistically significant effects of treatment on U.S. No. 2 yield may not be practically meaningful.

The percentage of marketable yield in tubers over six ounces was higher in subplots with a hilled-row configuration than those with a bed configuration. Subplots receiving 150 $lbs \cdot ac^{-1}$ total N had significantly less of their yield in tubers over six ounces than those receiving 200 or 250 $lbs \cdot ac^{-1}$ N. The percentage of yield represented by tubers over six or ten ounces was higher in low-density than high-density subplots.

Tuber quality

Results for tuber quality are presented in Table 3. The prevalence of hollow heart and brown center was somewhat higher in low-density subplots than high-density subplots, corresponding to the higher yields of large tubers observed at low density. Low-density subplots receiving 150 $lbs \cdot ac^{-1}$ N had an especially high prevalence of hollow heart, resulting in a marginally significant effect of the interaction between planting density and N rate.

The prevalence of scab was universally low, as expected with Russet Burbank, and not significantly related to treatment.

Tuber specific gravity and dry matter content were both significantly higher in subplots planted in beds than those planted in hilled rows, and both variables were higher at the lowest N rate (150 lbs·ac^{-1} N) than in the other two. Subplots at high planting density had higher tuber specific gravity and dry matter content than those planted at low density, but the difference was only marginally significant for specific gravity. The effect of planting density on tuber dry matter content was only evident in subplots with a bed configuration, as indicated by a significant effect of the interaction between configuration and density. In addition, the relationship between N rate and tuber dry matter content depended on both planting configuration and density, resulting in a significant effect of the interaction among configuration, density, and N rate.

Petiole NO_3^--N concentration

Results for petiole NO_3^--N concentration are presented in Table 4. Season-average petiole NO_3^--N concentrations were higher in hilled-row plots than in bed plots. Season-average concentrations were also higher in low-density subplots than high-density subplots. The subplots receiving 250 lbs·ac^{-1} N had higher season-average concentrations than the subplots receiving 200 lbs·ac^{-1} N, which had higher concentrations than the subplots receiving 150 lbs·ac^{-1} N. Averaged across treatments, petiole NO_3^--N concentration decreased between each sampling time and the next. Significant differences in petiole NO_3^--N concentration between bed and hilled-row plots and between low- and high-density subplots did not emerge until the second sampling date (July 20), and the effects of date*configuration and date*density were therefore both significant. The effect of N rate on NO_3^--N concentration were also less apparent on the first sampling date (July 2) than on the last two (July 20 and August 3), but the date*rate interaction was not quite statistically significant. These results are consistent with the results for marketable yield and tuber size, indicating that tuber size was limited by the availability of N to individual plants.

Soil water NO_3^--N

Results for soil water NO_3^--N concentration are presented in Table 5. The season-average soil water NO_3^--N concentration was higher in low-density subplots than in high-density subplots, suggesting that, collectively, the plants in high-density subplots were more efficient at intercepting N in the soil than the plants in low-density subplots. However, neither planting configuration nor the application rate of N were related to the concentration of NO_3^--N in the soil water, averaged across the season.

Due to numerous gaps on the soil water NO_3^--N data, entire treatment groups are absent from 6 of the 13 sampling dates. This both prevents the use of a repeated-measures analysis and makes the statistical results for those dates questionable. Nevertheless, there were two trends in the data that are likely to be meaningful. First, all treatments showed increases in soil water NO_3^--N concentration between the first and third sampling dates (June 24 and July 10). Second, the two treatments that had among the highest soil water NO_3^--N concentrations the most consistently were the treatments planted at low density and receiving the highest rate of N.

Vine and tuber N uptake and end-of-season soil NO_3^--N

Results for vine and tuber N uptake and end-of-season soil NO_3^--N are presented in Table 6. Vine N concentration was somewhat lower in bed plots than hilled-row plots and significantly lower in plots receiving 150 lbs·ac^{-1} N than in subplots receiving 200 or 250 lbs·ac^{-1} N. Tuber N concentration was lower in the subplots receiving 150 lbs·ac^{-1} N than those receiving higher N rates. Tuber N concentration was not otherwise significantly related to treatment.

Vine N uptake was significantly greater in hilled-row plots than bed plots, and it was significantly lower in subplots receiving 150 lbs·ac^{-1} N than subplots receiving higher rates o N. Tuber N uptake was marginally significantly greater in the hilled-row plots than the bed plots, but it was not otherwise related to treatment. Results for total (vine plus tuber) N uptake were substantially similar to results for vine N uptake alone.

In Russet Burbank plants grown for a typical processing season (120 days), vine N uptake is consistently quite small compared to tuber N uptake, representing perhaps 20% of the total. In this truncated season (85 days), vine and tuber N uptake were nearly equal, on average, and vine N uptake was generally greater than tuber N uptake in the hilled-row plots. This suggests that much of the N that would normally be translocated from vines to tubers in a full-length growing season still remained in the vines at vine kill in this study.

End-of-season soil NO_3^--N concentration was not significantly related to treatment.

Conclusions

Overall, planting at high density strongly favored the production of whole-seed-sized tubers at the expense of tubers marketable for processing compared to planting at low density, while the bed planting configuration had a similar, though less pronounced, effect relative to the hilled-row configuration. No treatment produced a commercially viable marketable yield, but this is attributable to the very late planting date (June 11) and short growing season (85 days to vine kill) relative to what Russet Burbank grown for processing requires (120 days). The results for N uptake strongly suggest that the plants had not finished translocating resources from vines to tubers by the time vines were killed.

The effects of the bed planting configuration, planting density, and N rate on tuber specific gravity were consistent with small tubers having higher specific gravity than large tubers. Specific gravity was higher in bed plots than hilled-row plots, higher at high density than low density, and higher at the lowest N rate than at the other two rates. Tuber dry matter content showed similar relationships, but with higher-order interaction effects that are difficult to explain. The weak effects of planting density on the prevalence of hollow heart and brown center may also be attributable to tuber size. Larger Russet Burbank tubers are more prone to these conditions, and both conditions were more prevalent at low planting density.

The results for petiole NO_3^--N indicate that individual plants were better able to acquire N in hilled rows than in beds, at low density than at high density, and at higher N rates than at lower rates. These results generally parallel those for tuber yield and size, indicating that N availability limited the ability of plants to bulk tubers in this study.

While individual plants in low-density subplots had higher petiole NO_3^--N concentrations than those in high-density subplots, the soil water in low-density subplots also had a higher NO_3^--N concentration, averaged across the season, than the soil water in high-density subplots. This indicates that the crop in low-density subplots is not more efficient at intercepting soil N than the crop in high-density subplots. Rather, individual plants at low density face less competition for N and are therefore each able to acquire more than individual plants at high density. However, the higher soil water NO_3^--N concentrations observed at low density did not translate into high end-of-season soil NO_3^--N concentrations, as this variable did not respond significantly to treatment.

There was no effect of planting density on vine or tuber N uptake, indicating that higher N uptake at the level of individual plants at low density roughly counterbalanced the lower number of plants taking up N. Instead, planting configuration and N rate were of much greater importance, with plants in beds taking up less N per acre than those in hilled rows and N uptake increasing with N rate. Notably, the effect of planting configuration was much more pronounced in vines than tubers, which may be a result of incomplete N translocation from vines to tubers in the short growing season.

Based on these results and those of the previous two years' research, the bed planting configuration is superior to the hilled-row configuration for producing whole seed tubers. In 2019, the bed configuration did not promote more efficient interception of soil N, as initially hypothesized, and therefore did not produce higher processing yields or tuber sizes than the traditional hilled-row configuration.

Table 1. Treatments applied to evaluate the effects of planting configuration, planting density, and N rate on whole seed tuber production by Russet Burbank potatoes grown near Staples, MN, in 2019.

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)	13000	24	150
			200
			250
	34000	9	150
			200
			250
Hilled row (row spacing 36.0 inches)	13000	14	150
			200
			250
	34000	5	150
			200
			250

[1] All treatments received 150 lbs·ac^{-1} N as 28% UAN throughout the season. In addition, the medium- and high-N treatments received 161 lbs·ac^{-1} DAP (18-46-0), plus 48 and 161 lbs·ac^{-1} ESN (44-0-0), respectively. The low-N treatment received 161 lbs·ac^{-1} TSP (0-48-0) to provide a similar rate of P_2O_5 to the other treatments.

Table 2. Effects of planting configuration, planting density, and N rate on tuber yield, size distribution, and grade of Russet Burbank potatoes grown near Staples, MN, in 2019.

Planting configuration	Planting density (seed pieces·ac^{-1})	Total N applied[1] (lbs·ac^{-1})	Tuber yield										
			0-4 oz	4-6 oz	6-10 oz	10-14 oz	> 14 oz	Total yield	#1s > 4 oz	#2s > 4 oz	Marketable yield	> 6 oz	> 10 oz
			cwt·ac^{-1}									%	
Bed	13000	150	216	105	32	0	0	356	130	5.1	135	9	0
		200	175	101	59	5	0	339	162	2.6	165	18	1.2
		250	186	113	35	8	0	341	155	0	155	12	2.2
	34000	150	265	41	6	0	0	308	48	0	48	2	0
		200	305	74	9	0	0	388	82	1.1	83	2	0
		250	274	72	5	0	0	351	77	0	77	1	0
Hilled row	13000	150	177	128	48	8	0	360	183	0.8	184	14	1.8
		200	179	109	69	14	2	373	194	0	194	22	4.1
		250	150	130	72	14	2	367	215	2.6	218	22	3.8
	34000	150	284	99	19	0	0	402	117	0.7	118	5	0
		200	233	79	27	3	0	341	107	0.7	108	9	0.8
		250	245	122	41	4	0	413	166	2.2	168	11	0.9
Significance of model effects (P-values)	Planting configuration		*0.0782*	**0.0017**	*0.0755*	0.2400	0.1724	0.1320	*0.0547*	0.6275	*0.0560*	*0.0677*	0.2036
	Planting density		**<0.0001**	**0.0002**	**<0.0001**	**0.0014**	0.1411	0.5669	**<0.0001**	*0.0617*	**<0.0001**	**<0.0001**	**0.0010**
	N rate		0.4444	0.1228	0.1073	0.1346	0.6189	0.8800	0.1048	0.7858	0.1107	**0.0447**	0.1115
	Configuration*density		0.8917	0.1922	0.8948	0.1922	0.2162	0.6976	0.6102	*0.0518*	0.5502	0.9636	0.1696
	Configuration*N rate		0.7418	0.1819	0.2233	0.8783	0.6189	0.4119	0.3248	**0.0094**	0.2787	0.3939	0.7672
	Density*N rate		0.9094	0.4842	0.3827	0.5860	0.7290	0.8004	0.8157	0.1758	0.8086	0.3555	0.4513
	Configuration*density*N rate		0.1591	0.5397	0.9154	0.8268	0.5255	0.1861	0.8430	0.1577	0.8556	0.8298	0.8452

[1] 150 lbs·ac^{-1} N as 28% UAN throughout the season, plus 161 lbs·ac^{-1} DAP (18-46-0) in the two higher-N treatments and 48 and 161 lbs·ac^{-1} ESN (44-0-0) in the medium- and high-N treatments, respectively.

Table 3. Effects of planting configuration, planting density, and N rate on tuber quality of Russet Burbank potatoes grown near Staples, MN, in 2019.

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	13000	150	3.4	1.2	0	1.0856	21.2 bcd
		200	0	0	0	1.0836	20.7 cde
		250	2.0	2.0	0.7	1.0810	20.5 def
	34000	150	0.5	0.8	1.0	1.0897	23.4 a
		200	0	0	0	1.0838	21.0 bcd
		250	0	0	0	1.0843	21.5 bc
Hilled row	13000	150	8.0	3.8	0	1.0843	21.8 b
		200	1.0	1.0	1.0	1.0807	19.6 f
		250	2.0	1.0	0	1.0796	20.0 ef
	34000	150	1.0	0	0	1.0828	20.8 cde
		200	3.0	0	0	1.0804	19.6 f
		250	0	1.0	0	1.0820	20.8 cde
Significance of model effects (P-values)	Planting configuration		0.1347	0.5486	0.7867	**0.0006**	**0.0001**
	Planting density		*0.0557*	*0.0734*	0.6722	*0.0937*	**0.0199**
	N rate		0.1186	0.3171	0.9688	**0.0007**	**<0.0001**
	Configuration*density		0.7158	0.5562	0.3775	0.1619	**0.0101**
	Configuration*N rate		0.5473	0.8526	0.2177	0.5311	0.5052
	Density*N rate		*0.0674*	0.6007	0.2101	0.3038	0.4328
	Configuration*density*N rate		0.4455	0.2637	0.2594	0.3735	**0.0187**

[1] 150 lbs·ac^{-1} N as 28% UAN throughout the season, plus 161 lbs·ac^{-1} DAP (18-46-0) in the two higher-N treatments and 48 and 161 lbs·ac^{-1} ESN (44-0-0) in the medium- and high-N treatments, respectively.

Table 4. Effects of planting configuration, planting density, and N rate on petiole NO_3^--N concentrations of Russet Burbank potato plants grown near Staples, MN, in 2019.

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	Season average
Bed	13000	150	20532	13545	4248	12775
		200	23197	14674	5527	14466
		250	24119	18088	9192	17133
	34000	150	22407	10604	3912	12308
		200	24596	14412	5049	14686
		250	25542	15353	5779	15558
Hilled row	13000	150	23689	17199	8286	16391
		200	25510	19861	9318	18230
		250	24027	20850	13211	19363
	34000	150	23044	10729	5916	13230
		200	25042	17881	8182	17035
		250	25897	21134	11901	19644
Average across treatments			23967 A	16194 B	7543 C	
Significance of model effects (P-values	Configuration					**<.0001**
	Density					**0.0443**
	N rate					**<.0001**
	Configuration*density					0.4386
	Configuration*N rate					0.7099
	Density*N rate					0.4795
	Configuration*density*N rate					0.1448
	Date		**<.0001**			
	Configuration*date		**0.0464**			
	Density*date		**0.0183**			
	N rate*date		0.1066			
	Configuration*density*date		0.8931			
	Configuration*N rate*date		0.5421			
	Density*N rate*date		0.4808			
	Configuration*density*N rate*date		0.9796			

[1] 150 lbs·ac^{-1} N as 28% UAN throughout the season, plus 161 lbs·ac^{-1} DAP (18-46-0) in the two higher-N treatments and 48 and 161 lbs·ac^{-1} ESN (44-0-0) in the medium- and high-N treatments, respectively.

Table 5. Effects of planting configuration, planting density, and N rate on soil water NO_3^--N concentrations in plots of Russet Burbank potato plants grown near Staples, MN, in 2019.

Planting configuration	Planting density (seed pieces·ac^{-1})	Total N applied[1] (lbs·ac^{-1})	Soil water NO_3^--N (ppm)													
			6/24	7/5	7/10	7/18	7/24	8/1	8/9	8/16	8/21	8/28	9/5	9/16	9/20	Season average
Bed	13000	150	9	23	40	45	31	40	44	35	33	27	54 bc	43	29	40
		200	22	29	40	45	30	26	47	37	39	34	50 bcd	33	45	36
		250	8	13	51	53	56	55	32	55	55	60	59 b	54	-	39
	34000	150	7	22	32	-	18	39	38	34	33	41	40 cde	43	52	35
		200	9	32	40	42	32	40	47	36	42	33	45 bcd	35	50	33
		250	9	18	30	41	28	36	35	37	32	23	32 de	37	-	26
Hilled row	13000	150	11	33	35	48	25	48	39	33	41	39	38 cde	33	63	36
		200	12	19	37	38	37	-	41	33	32	40	22 e	39	31	31
		250	8	-	-	46	35	45	-	56	48	52	61 b	48	75	45
	34000	150	11	30	43	47	32	29	38	43	25	32	37 de	49	45	27
		200	14	17	32	39	27	34	36	32	29	24	80 a	36	47	26
		250	8	20	32	46	35	32	40	30	31	26	24 e	42	62	33
Significance of model effects (P-values)	Planting configuration		0.9239	0.8756	0.8461	0.9189	0.9101	0.5990	0.4071	0.8135	0.3531	0.7914	0.6786	0.9322	0.7940	0.6204
	Planting density		0.4021	0.9315	0.1333	0.6645	0.2990	0.1889	0.6492	0.2590	*0.0663*	**0.0123**	0.2925	0.7884	0.7980	**0.0352**
	N rate		*0.0729*	0.1073	0.9748	0.2341	0.3879	0.3814	0.3576	0.2976	0.3608	0.3299	0.3362	0.3868	0.3293	0.5926
	Configuration*density		0.2646	0.6236	0.4796	0.6731	0.3702	0.5310	0.9902	0.9126	0.6300	0.3928	**0.0206**	0.5397	0.5400	0.7723
	Configuration*N rate		0.6219	**0.0294**	0.6536	0.3349	0.7828	0.8077	0.4402	0.8216	0.7180	0.9112	0.3441	0.9337	0.3059	0.2353
	Density*N rate		0.5268	0.8591	0.3054	0.6047	0.7576	0.1686	0.8097	0.1560	0.2272	**0.0128**	**0.0027**	0.2540	0.8539	0.5206
	Configuration*density*N rate		0.3333	0.8710	0.2197	0.4474	0.4594	0.1713	0.4445	0.7763	0.6298	0.2822	**0.0318**	0.7160	0.2194	0.9485

[1] 150 lbs·ac^{-1} N as 28% UAN throughout the season, plus 161 lbs·ac^{-1} DAP (18-46-0) in the two higher-N treatments and 48 and 161 lbs·ac^{-1} ESN (44-0-0) in the medium- and high-N treatments, respectively.

Table 6. Effects of planting configuration, planting density, and N rate on vine and tuber N concentration, N uptake into vines, tubers, and vines plus tubers, and end-of-season soil NO_3^--N concentrations in plots of Russet Burbank potato plants grown near Staples, MN, in 2019.

Planting configuration	**Planting density (seed pieces·ac^{-1})**	**Total N applied[1] (lbs·ac^{-1})**	**Vine N (%)**	**Tuber N (%)**	**Vine N uptake (lbs·ac^{-1})**	**Tuber N uptake (lbs·ac^{-1})**	**Total N uptake (lbs·ac^{-1})**	**End-of-season soil NO_3^--N**
Bed	13000	150	1.54	1.13	44	86	125	15
		200	2.02	1.19	60	84	144	18
		250	2.41	1.20	77	84	161	18
	34000	150	1.68	1.08	43	69	118	16
		200	2.17	1.05	63	86	150	16
		250	2.36	1.18	69	88	156	16
Hilled row	13000	150	2.33	1.08	83	84	167	17
		200	2.88	1.28	112	93	205	24
		250	3.20	1.38	137	100	237	18
	34000	150	2.50	1.04	93	87	180	19
		200	3.09	1.28	127	86	213	20
		250	2.84	1.25	129	107	237	21
Significance of model effects (P-values)	Planting configuration		*0.0891*	0.2943	**0.0502**	*0.0822*	**0.0227**	0.1366
	Planting density		0.8225	0.2319	0.7885	0.8437	0.8188	0.7698
	N rate		**0.0122**	**0.0335**	**0.0003**	0.1639	**0.0019**	0.3140
	Configuration*density		0.8487	0.8631	0.5833	0.6831	0.6927	0.7087
	Configuration*N rate		0.8390	0.2081	0.5785	0.6080	0.5990	0.6222
	Density*N rate		0.6455	0.9678	0.5731	0.6875	0.9373	0.5964
	Configuration*density*N rate		0.3383	0.6282	0.9293	0.5715	0.9275	0.3225

[1] 150 lbs·ac^{-1} N as 28% UAN throughout the season, plus 161 lbs·ac^{-1} DAP (18-46-0) in the two higher-N treatments and 48 and 161 lbs·ac^{-1} ESN (44-0-0) in the medium- and high-N treatments, respectively.