Nitrogen Response and Soil Microbial Activity in Potato Cropping Systems as Affected by Fumigation – Year 1

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Summary

Fumigation is commonly used by potato growers to control soil-borne pathogens. Its short-term benefits include improved disease control and healthier root systems, which may decrease nutrient input requirements. However, fumigation also eliminates beneficial soil organisms, which may depress the soil community's capacity for pathogen control and nutrient cycling. The goal of our research was to determine the interactive effects of fumigation and N application rate on soil microbial respiration and mineral N concentrations and Russet Burbank leaf greenness and tuber yield, size, quality, sucrose and glucose concentrations, and frying quality. We applied treatments in a split-plot randomized complete block design with four blocks. Whole plots received either Chloropicrin, Vapam, or no fumigant, and each whole plot was split into subplots, each receiving N at one of five total rates (including 40 lbs·ac^{-1} N as DAP at planting): (1) 40 lbs·ac^{-1}, 120 lbs·ac^{-1}, 180 lbs·ac^{-1}, 240 lbs·ac^{-1}, and 300 lbs·ac^{-1}. Fumigation treatments were applied in October and November 2015, and N treatments were applied at shoot emergence in 2016. Soil 24-hour CO_2 production, NH_4-N, and NO_3-N were determined for six-inch soil samples collected before fumigation in 2015 and before planting, during the growing season, and after harvest in 2016. Leaflet SPAD readings were taken at five times between hilling and harvest to measure leaf greenness. Tuber yield, size, quality, sugar concentrations, and frying quality were determined after harvest. Soil from the fumigated plots showed low rates of microbial respiration compared to the non-fumigated plots during the growing season but recovered to non-fumigated levels by harvest. The fumigated plots had elevated NH_4-N concentrations before planting, and the plots fumigated with Chloropicrin had high NH_4-N and low NO_3-N relative to the non-fumigated plots, indicating that fumigation may interfere with nitrification. Leaflet SPAD increased with N application rate but did not respond to fumigation treatment. Total and marketable yields were higher in the fumigated plots than in the non-fumigated plots, but did not plateau at lower N rates. However, the percentage of yield represented by tubers weighing over six ounces was higher and plateaued at a lower N rate in fumigated plots than in non-fumigated plots, suggesting that fumigation may decrease N requirements for tuber bulking but not for tuber yield. Tuber quality was not meaningfully related to fumigation treatment. The same was true of tuber sucrose and glucose concentrations and French fry reflectance in both the stem ends and bud ends of tubers. Stem-end sucrose concentration and the glucose concentration in both ends of the tuber decreased with increasing N application rate. Bud-end sucrose concentration and French fry reflectance increased with N rate, except that reflectance was relatively high for stem-end French fries from tubers grown at the lowest N rate. Overall, we found that while fumigation increased marketable yield at all N rates tested and decreased N requirements for tuber bulking, it lowered soil microbial activity/diversity during the growing season. Microbial activity was low in all treatments at harvest suggesting that soil improvement practices should be considered following a potato crop.

Background

Fumigation of potato fields to control pathogens has well-known short-term benefits. Most directly, fumigation decreases disease incidence. An apparent consequence of this is that potato plants in fumigated soil have healthier root systems, which may result in a decreased requirement for nutrient inputs. However, a major drawback of soil fumigation is that it eliminates beneficial soil organisms in addition to the pathogens. The benefits such organisms provide include pathogen control and nutrient cycling activities. Consequently, once a field is fumigated, additional applications of fumigant are required to control pathogens each time potatoes are planted in the field and nutrient cycling may be disrupted during and beyond the years when fumigant is applied.

The objectives of this study were to: 1) determine the effects of Vapam and Chloropicrin fumigation on potato response to N fertilizer, and 2) characterize the effect of fumigation on soil microbial activity and nitrogen transformations.

Methods

Study design

The study was conducted at the Sand Plain Research Farm in Becker, Minnesota, on a Hubbard loamy sand soil. The previous crop was soybeans. Potatoes have been grown at this site in a 3-year rotation without fumigation since 2000 with the last crop of potatoes grown in 2014. Fumigation treatments were arranged in a randomized complete block design with four blocks and three fumigation treatments. The fumigation treatments were: no fumigation with tillage on November 11, 2015; fumigation with Chloropicrin on October 14, 2015 at 100 lbs/A applied in strips followed by hilling; and fumigation with Vapam at 70 gallons/A injected at 6" and 10" on November 3, 2015.

Five N fertilization treatments were arranged as randomized subplots within each fumigation plot, as a split-plot randomized complete block design. Each subplot was 20 feet long and 21 feet wide. The subplots within each plot were separated by a 7-foot-wide alley running across the planting rows. All subplots received 40 $lbs \cdot ac^{-1}$ N as DAP at planting, plus 0, 80, 140, 200, or 260 $lbs \cdot ac^{-1}$ N as ESN at emergence, depending on the assigned N treatment.

The subplots were arranged in six columns and ten rows, with the columns running parallel to the planting rows for the length of the field (300 feet) and the rows running across the planting rows for the width of the field (150 feet). Two, 8-foot-wide alleys were placed between every two columns, and irrigation lines were placed along these alleys and the field edges (four lines in total, with 50-foot spacing between lines). A single alley was placed between the fifth and sixth rows of subplots, separating blocks 1 and 2 from blocks 3 and 4. This alley was 30 feet wide for most of its length, but only 10 feet wide between whole plots where Vapam was applied, because the size of the Vapam application equipment required these plots to be placed further from the ends of the field than originally planned. A summary of the treatments is presented in Table 1.

Soil sampling

Soil samples to a depth of 6 inches were collected on October 12, 2015, and April 19, July 6, and October 10, 2016. The samples were then dried at 95°C for 48 hours, ground, and extracted with 2N KCl. The extracts were analyzed for NH_4-N and NO_3-N concentrations using a Wescan nitrogen analyzer. Soil microbial respiration rates were determined on dried samples using Solvita Soil CO_2 Burst Test kits. Soil labile amino-N was measured for samples collected on October 12, 2015, and July 6, 2016, using a Solvita SLAN Test kit.

Planting and N treatments

The subplots were planted with Russet Burbank whole "B" seed potatoes on May 2, 2016, with one-foot spacing within rows and three-foot spacing between rows. Each subplot was seven rows wide. In each subplot, the fourth and fifth rows from the irrigation alley were designated as harvest rows. In these two rows, the first and last seed potato in each subplot was replaced with a Norland Red potato to identify the boundaries between subplots during harvest. Each adjacent pair of whole plots was surrounded by a buffer strip of Russet Burbank potato plants five feet wide on the ends and three feet (one row) wide along the sides. At row opening, 40 $lbs \cdot ac^{-1}$ N, 102 $lbs \cdot ac^{-1}$ P_2O_5, 181 $lbs \cdot ac^{-1}$ K_2O, 40 $lbs \cdot ac^{-1}$ S, 20 $lbs \cdot ac^{-1}$ Mg, 1 $lb \cdot ac^{-1}$ Zn, and 0.6 $lbs \cdot ac^{-1}$ B were banded in as a blend of DAP

(18-46-0), MOP (0-0-60), SulPoMag (0-0-22-20S-10Mg), BluMin (0-0-0-0.5S-1Zn), and Boron 15 (0-0-0-15).

Environmentally Smart Nitrogen (ESN; 44-0-0; Agrium, Inc.) was hand-broadcast on subplots per the assigned N treatments at shoot emergence, on June 2 and then hilled in.

Plant stand, leaflet SPAD readings, and petiole NO_3-N

For each plot, plant stand in the harvest rows and the number of stems per plant for ten plants in the harvest rows were recorded on June 8.

On 5 days throughout the summer, relative greenness in the terminal leaflet of the fourth leaf from the tip of 20 shoots per plot was recorded with a SPAD meter, generating a single average SPAD meter reading for each plot. SPAD readings were taken on June 16 and 23, July 6 and 19, and August 3 (i.e., 14, 21, 34, 47, and 62 days after the emergence fertilizer was applied).

On the same days that SPAD readings were collected, the petiole of the fourth leaf from the tip was collected from each of 20 shoots per plot. The petioles were dried at

*Harvest, tuber quality, and tuber sugars and fry colo*r

Tubers were harvested on September 28. They were sorted by size and USDA grade during the following week. Representative 25-tuber samples were evaluated for hollow heart, brown center, dry matter content, and specific gravity. Representative 20-tuber subsamples from each plot were sent to USDA-ARS (East Grand Forks, MN) to determine the sucrose and glucose concentrations of the stem and bud ends of the tubers. Samples from the stem and bud ends were French-fried by USDA, and their reflectances were determined using a Photovolt reflectometer.

Data analysis

The data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the MIXED procedure. For each dependent variable, fumigation treatment, N treatment, and their interaction were treated as fixed effects, and block and the interaction between block and fumigation treatment (the factor differentiating whole plots) were treated as random effects. Marginal means for dependent variables at each level of fumigation*nitrogen were determined using the LSMEANS statement, and post-hoc pairwise comparisons (alpha = 0.05) were conducted using the DIFF option. Pairwise comparisons are only presented where the significance (P-value) of fumigation, N treatment, or their interaction in the model is less than 0.05.

Results and discussion

Soil respiration

The results of 24-hour CO_2 burst tests (a measure of soil respiration) are presented in Table 2. 24-hour CO_2 production from soil samples collected on October 12, 2015, before fumigant or N treatments were applied, was related to N treatment. The subplots receiving 180 $lbs \cdot ac^{-1}$ total N had, on average, significantly lower CO_2 production than those receiving any other rate. Because N had not yet been applied, this effect was due to field variability within the experimental site.

Soil CO_2 production from samples collected on April 19, 2016, after fumigation treatments were applied but before N treatments were, was significantly related to fumigation treatment, with the plots receiving no fumigant having higher CO_2 production than those receiving Chloropicrin or Vapam, and the plots receiving Chloropicrin having higher CO_2 production than those receiving Vapam. In soil samples collected on July 6, 2016, after both fumigation and N treatments were applied, soil CO_2 production was significantly related only to fumigation treatment. The plots receiving no fumigant had higher CO_2 production than those receiving Chloropicrin or Vapam, which did not have significantly different CO_2 production from each other. Soil CO_2 production from samples collected on October 10, 2016, after harvest, was not significantly related to fumigation treatment, N treatment, or their interaction. Soil microbial activity as measured by CO_2 production decreased in the non-fumigated plots through the growing season, which may be due to low amounts of residues associated with the crop.

Soil NH_4-N and NO_3-N

Soil NH_4-N and NO_3-N concentration results are presented in Table 3. On October 12, 2015, before the fumigation treatments were applied, neither soil NH_4-N concentration nor soil NO_3-N concentration were related to fumigation treatment, N treatment, or their interaction. On April 17, 2016, several months after the fumigation treatments were applied but before any fertilizer applications, the treatments receiving Vapam or Chloropicrin had significantly higher soil NH_4-N and total mineral N concentrations than the non-fumigated treatments. No similar effect was seen for NO_3-N. On July 6, 34 days after ESN was applied at shoot emergence, soil mineral N concentrations increased with N application rate for all three fumigation treatments. The plots receiving Chloropicrin showed a much stronger response of NH_4-N to N rate than those receiving Vapam or no fumigant. They had a significantly higher mean NH_4-N concentration than the treatment receiving Vapam at an N application rate of 240 $lbs \cdot ac^{-1}$, and a higher concentration than either of the other treatments at 300 $lbs \cdot ac^{-1}$ N. The treatments receiving no fumigant had a significantly higher mean soil NO_3-N concentration than the fumigated treatments when N was applied at 300 $lbs \cdot ac^{-1}$, but not at other N rates. Both the non-fumigated treatments and the treatments receiving Chloropicrin showed similar responses of total soil mineral N to the application rate of N, but the treatments receiving Vapam showed a much weaker response of mineral N to the application rate of N. The treatments receiving Vapam had a significantly lower mean soil mineral N concentration than the treatments receiving Chloropicrin at an N application rate of 240 $lbs \cdot ac^{-1}$, and a lower mineral N concentration than either of the other fumigation treatments at 300 $lbs \cdot ac^{-1}$ N. On October 10, after tuber harvest, mineral N was unrelated to fumigation treatment, N treatment, and their interaction.

The elevated pre-planting NH_4-N concentrations of the fumigated plots and the tendency for mineral N to take the form of NH_4-N in plots treated with Chloropicrin may both be the results of a negative effect of soil fumigation on soil nitrification processes, which convert NH_4^+ to NO_3^-. This is consistent with the negative effect of fumigation on overall microbial respiration observed in the CO_2 burst tests. The positive effects of fumigation are to eliminate soil borne diseases. *Verticillium* assays were not available at the time of this report.

It is not clear why Vapam-treated plots showed weaker responses of soil mineral N to the application rate of N than plots treated with Chloropicrin or non-fumigated plots. Vapam-treated plots did not produce higher tuber yields than Chloropicrin-treated plots (see below). Perhaps plants in Vapam-treated plots took up more N, resulting in higher tissue N concentrations or vine biomass. Ongoing analyses will determine whether this is the case.

Plant stand and leaflet SPAD

Plant stand and leaflet SPAD results are presented in Table 4. Neither fumigation treatment nor N treatment were significantly related to plant stand six days after the emergence fertilizer was applied. There was an effect of the interaction between fumigation treatment and N treatment on the number of stems per plant, suggesting that plants responded differently to N treatment under different fumigation regimens. However, the number of stems per plant fluctuated apparently at random with increasing N application rate for all three fumigation treatments, and it is unlikely that this interaction effect is biologically significant.

SPAD readings, which indicate the relative density of chlorophyll per unit area in the measured leaflet, increased with N application rate on all five sampling dates. SPAD generally declined over time, while the response of SPAD to N rate grew stronger, especially at higher N rates. Fumigation treatment had no effect on SPAD. There was a significant effect of the interaction between fumigation treatment and N treatment on SPAD readings on the final sampling date, August 3. The plots receiving Chloropicrin had lower SPAD than the plots receiving no fumigant or Vapam in the low-N control subplots (40 lbs·ac^{-1} N), while the plots receiving Vapam had lower SPAD than the other two treatments in the highest-N subplots (300 lbs·ac^{-1} N).

Tuber yield, size, and grade

Tuber yield, size, and grade results are presented in Table 5. Nitrogen treatment had strong effects on tuber yield and size distribution that were largely consistent across fumigation treatments. Total and marketable yield were lower for the control treatments receiving only 40 lbs·ac^{-1} N than they were for any other treatment among plots receiving Vapam or no fumigation. The same trend was seen in the plots receiving Chloropicrin, except that the subplots receiving 180 or 300 lbs·ac^{-1} N did not have significantly greater total yield than the control subplots (though they did have greater marketable yield). Total and marketable yield showed weak responses to N application rate at rates between 180 and 300 lbs·ac^{-1} N regardless of fumigation treatment. There was no evidence that yields peaked at lower N rates for fumigated plots than for non-fumigated plots.

Fumigation treatment affected the yields of 6-10-ounce and 10-14-ounce tubers, as well as total yield, marketable yield, the yield of U.S. No. 2 tubers, and the proportion of yield represented by tubers weighing over 6 ounces. In each case, fumigated plots had higher values than the non-fumigated control plots. There was a marginally significant effect of the interaction between fumigation treatment and N treatment on the percentage of yield represented by tubers weighing over 6 ounces. The plots receiving either Chloropicrin or Vapam had more of their yields in tubers over six ounces than the non-fumigated plots did in the subplots receiving 40 to 180 lbs·ac^{-1} N, but not in the subplots receiving higher application rates.

Tuber quality

Tuber quality results are presented in Table 6. The prevalence of disqualifying hollow heart and brown center were related to fumigation treatment, N treatment, and their interaction. This was due to relatively high prevalence of both conditions in the subplots receiving no fumigant and 180 or 300 lbs·ac^{-1} N. It is possible that the likelihood of these conditions increase with N application rate only when no fumigant is applied, but it is not obvious why this should be the case. Tuber dry matter content was significantly related to the application rate of N. The subplots receiving 40 lbs·ac^{-1} N had lower dry matter content, on average, than those receiving 120 to 240 lbs·ac^{-1} N. Tuber specific gravity was not related to fumigation treatment, N treatment, or their interaction.

Tuber sugars and French fry color

Tuber sugar and French fry reflectance results are presented in Table 7. Fumigation treatment and its interaction with N application rate did not significantly affect tuber sucrose or glucose concentrations, nor the reflectance values observed for French fries made from the tubers.

The sucrose concentration of the stem end of the tuber generally decreased as the application rate of N increased, except that the subplots receiving Chloropicrin and 180 lbs·ac^{-1} N had the highest stem-end sucrose concentration in the study. The effect of N rate was especially pronounced between the lowest N rate (40 lbs·ac^{-1} N) and the second lowest (120 lbs·ac^{-1} N). In contrast to stem-end sucrose, bud-end sucrose tended to increase as N application rate increased, though this positive relationship was weaker than the negative relationship observed for stem-end sucrose. Sucrose concentrations were over an order of magnitude higher in the bud ends of tubers than in the stem ends.

Concentrations of glucose decreased with increasing N application rate in both the stem ends and the bud ends of tubers. The effect of N rate was stronger at lower application rates, but, especially in bud end tissue, N rate affected tuber glucose concentration across the range of application rates tested. Glucose concentrations were about three times as high in the stem ends of tubers as in the bud ends.

The reflectance of French fries made from the bud ends of tubers increased with increasing N application rate, especially at application rates between 40 and 180 $lbs \cdot ac^{-1}$ N. The same was true for French fries made from the stem ends of tubers for N rates between 180 and 300 $lbs \cdot ac^{-1}$ N, but reflectance decreased with increasing N application rate for rates between 40 and 120 $lbs \cdot ac^{-1}$ N. The cause of relatively high reflectance scores at 40 $lbs \cdot ac^{-1}$ N is uncertain, though perhaps the stem ends of these tubers lack sufficient asparagine for a more robust Maillard reaction to darken the French fries. French fries made from the bud end of the tuber had approximately 60% higher reflectance than those made from the stem end, indicating lighter fries. This is probably a direct consequence of the lower glucose concentrations observed in the bud ends of tubers compared to the stem ends.

Conclusions

Based on our results for soil respiration, fumigation decreases overall soil microbial activity significantly. Our soil NH_4-N and NO_3-N concentration results indicate that nitrification, in particular, is inhibited by fumigation. Our yield results indicate an advantage of fumigation in terms of tuber yield and size. However, tuber yield did not plateau at a lower application rate for fumigated plots than for non-fumigated plots, although the percentage of yield represented by tubers over six ounces did, suggesting that fumigation may decrease N requirements for tuber bulking, but not for yield. The concentration of glucose (a reducing sugar) in the tuber decreased as N application rate increased, but fumigation had no effect on this relationship. Overall, fumigation treatment appeared to affect soil N cycling processes and overall microbial activity, but fumigated plots had higher tuber yields and larger tubers than non-fumigated plots.

Table 1. Fumigation and N treatments applied to irrigated Russet Burbank potatoes at the Sand Plain Research Farm in Becker, MN, in 2016.

Fumigation treatment (whole plots)	Nitrogen applicaton rate, $lbs \cdot ac^{-1}$ (subplots)	
	Emergence (ESN)[1]	Total[2]
None	0	40
	80	120
	140	180
	200	240
	260	300
Chloropicrin	0	40
	80	120
	140	180
	200	240
	260	300
Vapam	0	40
	80	120
	140	180
	200	240
	260	300

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

[2]Each plot received 40 lbs·ac-1 N at planting as MAP (18-46-0)

Table 2. Effects of fumigation and N treatments on soil microbial respiration, as measured by CO_2 production in a 24-hour period at 70°F using a Solvita CO_2 Burst Test kit, and on soil labile amino N concentration, as measured by NH_3 released in a 24-hour period at 70°F in an alkali solution using a Solvita SLAN kit. Values within the same column that have a letter in common are not significantly different from each other (i.e. $P > 0.05$). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Fumigation treatment	Nitrogen application rate (lbs/ac)	Solvita CO_2 burst test results (ppm increase in CO2 after 24 hours incubation at 70°F)				SLAN test reading (proportional to labile amino N concentration)	
		October 12, 2015	April 19, 2016	July 6, 2016	October 10, 2016	October 12, 2015	July 6, 2016
Control	40	56.0	40.9	30.6	22.7	4.51	4.39 ab
	120	48.0	39.4	36.8	17.3	4.52	4.41 ab
	180	42.8	36.4	21.0	17.7	4.50	4.35 bc
	240	60.9	33.9	39.0	23.5	4.47	4.25 cd
	300	50.0	34.1	25.3	25.8	4.43	4.24 cd
Chloropicrin	40	56.2	35.1	11.0	13.7	4.50	4.43 ab
	120	54.3	31.8	12.0	26.0	4.45	4.29 bcd
	180	33.6	26.4	11.9	17.7	4.49	4.30 bc
	240	60.1	30.8	8.6	15.3	4.45	4.16 d
	300	54.5	24.5	16.5	17.4	4.55	3.84 e
Vapam	40	63.1	18.4	18.9	29.6	4.45	4.42 ab
	120	53.0	20.5	13.1	17.6	4.51	4.49 a
	180	42.5	16.4	11.3	19.1	4.55	4.35 bc
	240	48.7	23.2	13.2	24.8	4.46	4.38 abc
	300	48.3	20.4	13.9	21.4	4.56	4.33 bc
Fumigation*Nitrogen (P-value)		0.7428	0.8617	0.1662	0.1751	0.1300	**0.0043**
Fumigation treatment	None	51.6	36.9 a	30.5 a	21.4	4.49	4.33 a
	Chloropicrin	51.7	29.7 b	12.0 b	18.0	4.49	4.20 b
	Vapam	51.1	19.8 c	14.1 b	22.5	4.51	4.39 a
Fumigation significance (P-value)		0.9936	**0.0049**	**0.0002**	0.2158	0.8643	**0.0132**
N application rate (lbs/ac total)	40	58.4 a	31.4	20.2	22.0	4.49	4.41 a
	120	51.8 a	30.6	20.6	20.3	4.49	4.40 a
	180	39.6 b	26.4	14.7	18.2	4.51	4.33 ab
	240	56.6 a	29.3	20.3	21.2	4.46	4.26 b
	300	51.0 a	26.3	18.6	21.5	4.51	4.14 c
Nitrogen significance (P-value)		**0.0130**	0.4729	0.4136	0.8030	0.2864	**<0.0001**

Table 3. Effects of fumigation and N treatments on NH_4-N and NO_3-N concentrations in the top six inches of soil on October 12, 2015, and April 19, July 6, and October 10, 2016, in plots used to grow Russet Burbank potatoes at the Sand Plain Research Farm in Becker, MN. Values within the same column that have a letter in common are not significantly different from each other (i.e. $P > 0.05$). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Fumigation treatment	**Nitrogen application rate (lbs/ac)**	Soil mineral N (ppm)											
		October 12, 2015			April 19, 2016			July 6, 2016			October 10, 2016		
		NH_4-N	NO_3-N	Total	NH_4-N	NO_3-N	Total	NH_4-N	NO_3-N	Total	NH_4-N	NO_3-N	Total
Control	40	1.9	6.1	8.0	2.2	4.7	7.0	1.5 e	3.7 c	5.2 e	0.4	3.1	3.5
	120	1.8	5.6	7.4	1.7	5.6	7.7	3.2 cde	6.2 c	9.5 cde	0.6	3.6	4.1
	180	1.8	6.2	8.0	2.0	5.5	7.5	5.5 cde	16.6 bc	22.3 bcde	0.3	4.9	5.3
	240	1.8	6.2	8.0	2.4	4.8	7.2	9.8 bc	17.0 bc	26.8 bc	0.4	5.3	5.6
	300	2.0	7.0	9.0	2.3	5.7	8.0	8.5 cd	47.0 a	55.5 a	0.6	4.3	4.9
Chloropicrin	40	2.0	5.5	7.5	6.4	7.2	13.6	1.7 de	5.7 c	7.4 de	0.6	4.1	4.7
	120	2.0	6.2	8.2	7.2	6.9	14.1	5.3 cde	9.6 bc	14.9 cde	0.5	3.9	4.4
	180	1.8	6.0	7.8	6.6	5.7	12.3	7.5 cde	9.8 bc	17.3 cde	0.6	4.8	5.4
	240	1.9	5.9	7.8	6.5	6.5	13.0	16.8 b	19.4 bc	36.2 b	0.6	5.3	5.9
	300	1.7	5.4	7.1	7.4	6.1	13.5	31.8 a	25.2 b	57.1 a	0.4	6.3	6.9
Vapam	40	1.8	5.6	7.4	6.0	6.2	12.2	2.0 de	6.4 c	8.4 de	0.5	4.2	4.7
	120	1.8	5.8	7.7	4.8	5.9	12.0	2.1 de	11.5 bc	13.6 cde	0.6	3.7	4.2
	180	1.6	5.2	6.9	3.6	4.6	8.9	5.5 cde	13.0 bc	18.5 bcde	0.5	3.2	3.7
	240	1.8	6.1	7.9	4.3	6.1	10.4	1.7 de	12.7 bc	14.4 cde	0.6	3.0	3.7
	300	1.9	5.5	7.3	5.4	4.9	10.3	6.9 cde	16.8 bc	23.7 bcd	0.6	3.3	3.8
Fumigation*Nitrogen (P-value)		0.9046	0.4521	0.4000	0.7284	0.2782	0.9003	**<0.0001**	**0.0144**	*0.0611*	0.5929	0.1516	0.1548
Fumigation treatment	None	1.9	6.2	8.1	2.1 c	5.3	7.5 c	5.7 b	18.1	23.9 a	0.4	4.2	4.7
	Chloropicrin	1.9	5.8	7.7	6.8 a	6.5	13.3 a	12.6 a	14.0	26.6 a	0.6	4.9	5.5
	Vapam	1.8	5.6	7.4	4.8 b	5.5	10.8 b	3.6 b	12.1	15.7 b	0.6	3.5	4.0
Fumigation significance (P-value)		0.7169	0.1278	0.1616	**0.0004**	0.1537	**<0.0001**	**0.0023**	0.2642	**0.0267**	0.1913	0.1151	0.1001
N application rate (lbs/ac total)	40	1.9	5.7	7.6	4.9	6.0	10.9	1.7 d	5.3 c	7.0 d	0.5	3.8	4.3
	120	1.9	5.9	7.8	4.6	6.1	11.3	3.5 cd	9.1 bc	12.7 cd	0.6	3.7	4.2
	180	1.7	5.8	7.6	4.1	5.3	9.6	6.2 bc	13.1 bc	19.4 bc	0.5	4.3	4.8
	240	1.8	6.0	7.9	4.4	5.8	10.2	9.4 b	16.4 b	25.8 b	0.5	4.5	5.1
	300	1.9	6.0	7.8	5.1	5.6	10.6	15.7 a	29.7 a	45.4 a	0.6	4.7	5.2
Nitrogen significance (P-value)		0.6481	0.9066	0.9267	0.5010	0.3357	0.2962	**<0.0001**	**0.0001**	**<0.0001**	0.5976	0.3153	0.2627

Table 4. Effects of fumigation and N treatment on plant stand and stems per plant on June 2 and leaflet SPAD readings (chlorophyll concentration) on five dates in 2016 for Russet Burbank potatoes at the Sand Plain Research Farm in Becker, MN. Values within the same column that have a letter in common are not significantly different from each other (i.e. P > 0.05). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Fumigation treatment	**Nitrogen application rate (lbs/ac)**	**Early-season vigor (June 8)**		**SPAD readings**				
		Stand (%)	**Stems / plant**	**June 16**	**June 23**	**July 6**	**July 19**	**August 3**
Control	40	100.0	3.9 abcd	39.2	35.1	31.6	30.0	23.2 f
	120	100.0	3.8 bcd	42.4	42.0	39.6	34.6	27.7 e
	180	100.0	4.2 ab	42.7	44.4	40.9	37.1	33.8 d
	240	99.3	3.5 d	44.0	46.1	42.7	38.8	37.8 c
	300	99.3	3.9 abcd	43.7	44.6	44.0	41.3	41.0 ab
Chloropicrin	40	100.0	4.1 abc	39.9	36.6	32.2	32.2	21.2 g
	120	100.0	3.4 d	41.6	42.9	37.9	34.8	28.5 e
	180	100.0	3.7 bcd	41.7	45.0	42.0	37.9	34.5 d
	240	100.0	4.4 a	42.9	45.5	43.8	38.5	38.5 c
	300	100.0	4.2 ab	42.9	45.9	43.6	41.8	42.2 a
Vapam	40	100.0	3.7 bcd	38.9	36.5	33.8	30.7	23.2 f
	120	100.0	3.6 cd	42.2	43.4	41.0	35.1	28.7 e
	180	100.0	4.0 abcd	43.4	46.0	41.8	37.0	33.8 d
	240	100.0	3.6 bcd	42.3	46.7	43.9	38.8	38.9 c
	300	99.3	3.9 abcd	43.5	45.4	44.0	40.9	39.3 bc
Fumigation*Nitrogen (P-value)		0.6892	**0.0426**	0.1225	0.8543	0.3089	0.9610	**0.0177**
Fumigation treatment	None	99.7	3.9	42.4	42.4	39.8	36.4	32.7
	Chloropicrin	100.0	4.0	41.8	43.2	39.9	37.0	33.0
	Vapam	99.9	3.7	42.1	43.6	40.9	36.5	32.8
Fumigation significance (P-value)		0.4219	0.3850	0.4070	0.2519	0.4690	0.5567	0.7754
N application rate (lbs/ac total)	40	100.0	3.9 a	39.3 d	36.1 d	32.5 d	31.0 e	22.5 e
	120	100.0	3.6 b	42.1 c	42.8 c	39.5 c	34.8 d	28.3 d
	180	100.0	3.9 a	42.6 bc	45.1 b	41.6 b	37.3 c	34.0 c
	240	99.8	3.8 a	43.0 ab	46.1 a	43.5 a	38.7 b	38.4 b
	300	99.5	4.0 a	43.4 a	45.3 ab	43.9 a	41.3 a	40.8 a
Nitrogen significance (P-value)		0.1955	*0.0862*	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**

Table 5. Effects of fumigation and N treatment on tuber yield, grade, and size for Russet Burbank potatoes grown at the Sand Plain Research Farm in Becker, MN, in 2016. Values within the same column that have a letter in common are not significantly different from each other (i.e. P > 0.05). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Fumigation treatment	**Nitrogen application rate (lbs/ac)**	**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}									**%**	
Control	40	76	234	53	2	0	364	183	105	288	15 f	1
	120	40	186	183	38	6	454	308	106	414	50 d	10
	180	36	183	204	58	8	489	355	98	453	55 cd	14
	240	35	138	201	72	24	471	331	105	436	63 abc	21
	300	34	122	187	94	29	466	344	88	432	66 a	26
Chloropicrin	40	58	273	140	13	2	485	249	178	427	31 e	3
	120	29	179	243	72	12	535	357	149	506	61 abc	16
	180	40	172	226	66	21	526	345	141	486	60 abc	17
	240	39	154	244	83	25	544	377	129	505	64 ab	20
	300	39	144	222	90	24	520	339	142	481	65 ab	22
Vapam	40	57	245	111	10	0	423	197	169	366	28 e	2
	120	34	189	236	55	5	519	300	185	485	57 bcd	12
	180	30	159	226	98	28	541	341	170	511	65 ab	23
	240	36	154	236	89	25	540	310	194	504	65 ab	21
	300	35	142	225	95	44	540	358	147	505	67 a	26
Fumigation*Nitrogen (P-value)		0.1410	0.2787	0.5002	0.1124	0.2909	0.2111	0.4700	0.6962	0.1592	*0.0663*	0.2645
Fumigation treatment	None	44	173	166 b	53 b	13	449 b	304	100 b	405 b	50 b	14
	Chloropicrin	41	184	215 a	65 a	17	522 a	333	148 a	481 a	56 a	15
	Vapam	38	178	207 a	69 a	20	512 a	301	173 a	474 a	56 a	17
Fumigation significance (P-value)		0.3500	0.2479	**0.0032**	**0.0096**	0.1806	**0.0006**	0.1165	**0.0045**	**0.0004**	**0.0007**	0.2734
N application rate (lbs/ac total)	40	64 a	250 a	101 b	8 d	1 c	424 b	210 b	151	360 b	25 d	2 d
	120	34 b	185 b	221 a	55 c	8 c	502 a	322 a	146	468 a	56 c	12 c
	180	35 b	171 b	219 a	74 b	19 b	519 a	347 a	136	483 a	60 b	18 b
	240	37 b	149 c	227 a	81 b	25 ab	518 a	339 a	142	482 a	64 a	21 b
	300	36 b	136 c	212 a	93 a	32 a	509 a	347 a	125	473 a	66 a	25 a
Nitrogen significance (P-value)		**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.4556	**<0.0001**	**<0.0001**	**<0.0001**

Table 6. Effects of fumigation and N treatment on the prevalence of hollow heart and brown center, tuber dry matter content, and tuber specific gravity for Russet Burbank potatoes grown at the Sand Plain Research Farm in Becker, MN, in 2016. Values within the same column that have a letter in common are not significantly different from each other (i.e. P > 0.05). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Fumigation treatment	Nitrogen application rate (lbs/ac)	Tuber quality				
		Hollow heart (%)	Brown center (%)	Scab (%)	Dry matter content (%)	Specific gravity
Control	40	0 c	0 c	0.0	21.1	1.0719
	120	0 c	0 c	3.8	23.0	1.0751
	180	14 a	14 a	0.0	21.9	1.0774
	240	4 bc	4 bc	0.0	22.6	1.0799
	300	7 b	8 b	1.1	22.6	1.0738
Chloropicrin	40	0 c	0 c	0.0	21.4	1.0741
	120	3 bc	3 bc	2.5	21.8	1.0803
	180	2 bc	2 c	0.0	22.7	1.0737
	240	3 bc	3 bc	0.0	22.0	1.0755
	300	1 bc	1 c	4.0	21.6	1.0779
Vapam	40	0 c	0 c	7.5	21.8	1.0769
	120	0 c	0 c	3.2	23.1	1.0788
	180	5 bc	5 bc	5.7	23.2	1.0821
	240	0 c	0 c	3.8	22.5	1.0804
	300	0 c	0 c	5.8	21.4	1.0750
Fumigation*Nitrogen (P-value)		*0.0789*	*0.0504*	0.9543	0.2656	0.3428
Fumigation treatment	None	5 a	5 a	1.0 b	22.2	1.0756
	Chloropicrin	2 b	2 b	1.3 b	21.9	1.0763
	Vapam	1 b	1 b	5.2 a	22.4	1.0787
Fumigation significance (P-value)		**0.0474**	*0.0516*	*0.0750*	0.2551	0.2529
N application rate (lbs/ac total)	40	0 b	0 b	2.5	21.4 c	1.0743
	120	1 b	1 bc	3.2	22.6 a	1.0781
	180	7 a	7 a	1.9	22.6 a	1.0777
	240	2 b	2 b	1.3	22.3 ab	1.0786
	300	3 b	3 b	3.7	21.9 bc	1.0756
Nitrogen significance (P-value)		**0.0071**	**0.0054**	0.8895	**0.0139**	0.2035

Table 7. Effects of fumigation and N treatment on stem-end and bud-end tuber sucrose and glucose concentrations and the reflectance of French fries made from the stem ends and bud ends of tubers of Russet Burbank potato plants grown at the Sand Plain Research Farm in Becker, MN, in 2016. Measurements were made at harvest (0 months) and after 3 and 7 months' storage at 48°F. Values within the same column that share a letter are not significantly different from each other (i.e. P > 0.05). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Fumigation treatment	Nitrogen application rate (lbs/ac)	Sucrose (mg/mL)						Glucose (mg/mL)						Reflectance (Photovolt reflectometer)					
		Stem			Bud			Stem			Bud			Stem			Bud		
		0 months	3 months	7 months	0 months	3 months	7 months	0 months	3 months	7 months	0 months	3 months	7 months	0 months	3 months	7 months	0 months	3 months	7 months
Control	40	0.065	0.354	0.330	0.424	0.572	0.501	2.649	2.309	2.677	0.958	0.760 bc	0.631	25.8	23.6	24.7	40.4	37.3	41.8
	120	0.020	0.318	0.295	0.503	0.540	0.501	2.194	2.178	3.100	0.705	0.833 ab	0.406	24.0	20.6	23.3	38.0	34.0	42.4
	180	0.000	0.257	0.310	0.483	0.563	0.490	2.224	2.073	2.338	0.617	0.456 def	0.378	25.3	20.5	25.8	43.6	39.0	41.5
	240	0.004	0.274	0.314	0.512	0.536	0.554	1.883	1.824	2.119	0.527	0.530 cdef	0.436	25.9	19.0	26.8	45.2	40.2	41.9
	300	0.009	0.292	0.324	0.516	0.627	0.515	1.843	1.575	2.072	0.497	0.424 def	0.338	28.6	20.9	26.7	41.8	42.5	43.2
Chloropicrin	40	0.038	0.305	0.355	0.440	0.575	0.520	2.500	2.617	2.700	1.047	0.686 bcd	0.926	26.7	22.6	24.5	40.7	36.9	40.2
	120	0.021	0.292	0.336	0.486	0.623	0.613	2.040	2.014	2.786	0.680	0.292 f	0.492	25.3	20.5	24.2	40.6	40.6	40.5
	180	0.075	0.254	0.286	0.398	0.565	0.572	1.634	1.570	1.743	0.650	0.347 ef	0.270	25.0	24.1	26.9	42.7	40.0	42.0
	240	0.020	0.200	0.244	0.492	0.562	0.505	1.895	1.772	1.890	0.579	0.532 cdef	0.397	24.4	18.7	26.3	44.4	39.7	42.2
	300	0.005	0.299	0.290	0.510	0.596	0.570	1.869	1.632	2.025	0.469	0.518 cdef	0.496	26.1	21.5	26.7	45.1	38.5	42.5
Vapam	40	0.034	0.394	0.427	0.405	0.538	0.541	2.766	2.545	3.028	1.216	1.053 a	0.870	26.4	23.1	24.7	34.6	34.3	39.4
	120	0.010	0.280	0.382	0.476	0.527	0.556	2.210	2.280	2.352	0.740	0.660 bcd	0.598	25.3	21.9	24.8	42.7	36.5	42.0
	180	0.025	0.134	0.356	0.478	0.588	0.642	1.987	2.183	2.281	0.630	0.476 cdef	0.485	23.9	20.9	25.9	43.3	41.9	42.2
	240	0.000	0.236	0.267	0.502	0.575	0.577	1.925	1.940	2.444	0.520	0.595 bcde	0.298	26.5	21.0	25.1	44.1	40.0	42.5
	300	0.000	0.212	0.351	0.576	0.631	0.560	1.947	1.880	1.499	0.374	0.357 ef	0.474	26.7	21.5	28.3	42.3	41.1	41.9
Fumigation*Nitrogen (P-value)		0.3508	0.3266	0.7786	0.9344	0.8401	0.8186	0.2391	0.1914	0.1101	0.9001	**0.0353**	0.6180	0.6116	0.1819	0.7007	0.1968	0.1736	0.9526
Fumigation treatment	None	0.020	0.299	0.315	0.488	0.567	0.512	2.158	1.992	2.461	0.661	0.600 ab	0.438	25.9	20.9	25.5	41.8	38.6	42.2
	Chloropicrin	0.032	0.270	0.302	0.465	0.584	0.556	1.988	1.921	2.229	0.685	0.475 b	0.516	25.5	21.5	25.7	42.7	39.1	41.5
	Vapam	0.014	0.251	0.357	0.487	0.572	0.575	2.167	2.166	2.321	0.696	0.628 a	0.545	25.8	21.7	25.8	41.4	38.7	41.6
Fumigation significance (P-value)		0.4824	0.1926	0.1687	0.7177	0.8124	0.1913	0.3153	0.1158	0.3886	0.9063	**0.0451**	0.4787	0.8098	0.4268	0.8728	0.5566	0.8797	0.7707
N application rate (lbs/ac total)	40	0.046 a	0.351 a	0.371 a	0.423 c	0.562	0.521	2.639 a	2.490 a	2.802 a	1.074 a	0.833 a	0.809 a	26.3 ab	23.1 a	24.6 bc	38.6 b	36.2 c	40.5
	120	0.017 bc	0.297 ab	0.338 ab	0.488 abc	0.563	0.557	2.148 b	2.158 b	2.746 a	0.708 b	0.595 b	0.498 b	24.9 bc	21.0 bc	24.1 c	40.5 b	37.0 bc	41.6
	180	0.033 ab	0.215 c	0.318 ab	0.453 bc	0.572	0.568	1.948 c	1.942 bc	2.121 b	0.632 bc	0.426 c	0.378 b	24.7 c	21.8 ab	26.2 a	43.2 a	40.3 a	41.9
	240	0.008 c	0.237 bc	0.275 b	0.502 ab	0.557	0.545	1.901 c	1.846 cd	2.151 b	0.542 cd	0.552 bc	0.377 b	25.6 bc	19.6 c	26.1 ab	44.6 a	39.9 ab	42.2
	300	0.005 c	0.268 bc	0.322 ab	0.534 a	0.618	0.548	1.886 c	1.695 d	1.865 b	0.447 d	0.433 bc	0.436 b	27.1 a	21.3 b	27.3 a	43.1 a	40.7 a	42.6
Nitrogen significance (P-value)		**0.0394**	**0.0020**	*0.0773*	*0.0707*	0.4139	0.8635	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0002**	*0.0615*	**0.0014**	**0.0012**	**0.0016**	**0.0075**	0.4193