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

Carl Rosen and Linda Kinkel
Department of Soil, Water, and Climate
Department of Plant Pathology
University of Minnesota

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Executive Summary

Carl Rosen[a], James Crants[a], Matt McNearney[a], Linda Kinkel[b], JP Dundore-Arias[b],

[a]Department of Soil, Water, and Climate; University of Minnesota
[b]Department of Plant Pathology, University of Minnesota

Fumigation is commonly used to control soil-borne pathogens in potato fields. 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 capacity of the soil microbial community to control pathogens and facilitate nutrient cycling. The goal of our research was to determine the effects of fumigation and fumigation source on N response and disease prevalence in Russet Burbank potatoes. 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.

The two-year study was conducted at the Sand Plain Research Farm in Becker, Minnesota, on a Hubbard loamy sand soil in 2016 and 2017. Treatments were applied in a split-plot randomized complete block design with four blocks. Whole plots received either Chloropicrin, Vapam, or no fumigant. Each whole plot was split into five subplots, each receiving N at one of five total rates (including 40 lbs·ac^{-1} N as DAP at planting): 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 2015 and November 2016 at the rates of 70 gal·ac^{-1} Vapam and 100 lbs·ac^{-1} Chloropicrin. Nitrogen treatments as Environmentally Smart Nitrogen (ESN: 44-0-0; Agrium, Inc.) were applied at emergence. Plant responses to treatment were evaluated in terms of tuber yield and N uptake. Soil responses were measured in terms of microbial respiration (CO_2 produced in 24 hours, a measure of microbial activity), NH_4-N concentration, and NO_3-N concentration.

Fumigation significantly decreased the concentration of *Verticillium* propagules in the soil in both years. It also decreased the severity of *Verticillium* wilt observed in late summer. The severity of *Verticillium* wilt also decreased with increasing N application rate in each year, suggesting that greater plant vigor in the fumigated plots partially explains the diminished wilt severity observed in these plots.

In both 2016 and 2017, total and marketable yields were lower in the non-fumigated plots than plots receiving either fumigant. In 2017, but not in 2016, plots receiving Vapam had higher total and marketable yields than plots receiving Chloropicrin, averaged across N rates. In both years, yield increased with increasing N rate, regardless of fumigation treatment, but yield did not change significantly across N rates of 180 to 300 lbs·ac^{-1} N. Based on a quadratic N response function, fumigation decreased the estimated N application rate at which peak yield was achieved, from 251 lbs·ac^{-1} N for the non-fumigated plots to 229 lbs·ac^{-1} N for the Chloropicrin-treated plots and 224 lbs·ac^{-1} N for the Vapam-treated plots, based on combined data from both years.

While fumigated and non-fumigated plots had similar rates of microbial respiration prior to fumigation, the non-fumigated plots had significantly higher respiration rates at planting and mid-season than the plots receiving either fumigant in both years. The effect of fumigation on

microbial respiration was no longer significant by October in 2016, but in 2017, the non-fumigated plots continued to have significantly higher microbial respiration rates than the plots treated with Vapam, with the Chloropicrin-treated plots intermediate. Nitrogen application rate was related to microbial respiration rate in both years (though only weakly in 2017), but the effect was inconsistent between years and difficult to interpret in each.

In each year, the fumigated plots, especially those treated with Chloropicrin, had high soil NH_4-N and low soil NO_3-N relative to the non-fumigated plots, indicating that fumigation interferes with nitrification. Soil NH_4-N and NO_3-N concentrations increased with the application rate of N in July of each year, but not at other times, indicating that the effect of N fertilization on soil mineral N concentrations did not persist beyond harvest.

Nitrogen uptake was greater in the fumigated plots than the non-fumigated plots in both 2016 and 2017. This difference was due to a difference in biomass production, especially tuber yield, rather than a difference in tissue N concentrations. Nitrogen uptake also increased with N application rate. Averaged across both years and relative to the non-fumigated plots, fumigation increased N uptake at the recommended N application rate of 240 $lbs \cdot ac^{-1}$ N by 45 $lbs \cdot ac^{-1}$ N in Chloropicrin-treated plots and 52 $lbs \cdot ac^{-1}$ N in Vapam-treated plots.

Overall, while fumigation suppressed microbial soil activity and inhibited nitrification, it was also effective in controlling *Verticillium* wilt, and it was presumably effective against other pathogens as well. The net result was that fumigated plots had higher yields, achieved peak yield at lower application rates of N, and took up more N at a given application rate than non-fumigated plots in both years of the study. Higher uptake of N with fumigation will reduce soluble or residual N in the soil as well as the potential for nitrate leaching. A major long-term goal in soil science is to obtain the benefits of fumigation, in terms of pathogen control and yield, without the negative impacts on the non-pathogenic components of the soil microbial community.

Nitrogen Response and Soil Microbial Activity in Potato Cropping Systems as Affected by Fumigation – Year 2

Carl Rosen[a], James Crants[a], Matt McNearney[a], Linda Kinkel[b], JP Dundore-Arias[b],
[a]Department of Soil, Water, and Climate; University of Minnesota
[b]Department of Plant Pathology, University of Minnesota

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 effects of fumigation and fumigation source on N response and disease prevalence in Russet Burbank potatoes. 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 $lbs \cdot ac^{-1}$ N as DAP at planting): 40 $lbs \cdot ac^{-1}$, 120 $lbs \cdot ac^{-1}$, 180 $lbs \cdot ac^{-1}$, 240 $lbs \cdot ac^{-1}$, and 300 $lbs \cdot ac^{-1}$. Fumigation treatments were applied in October and November 2016, and N treatments as Environmentally Smart Nitrogen (ESN: 44-0-0; Agrium, Inc.) were applied at emergence, on May 11, 2017. Soil 24-hour CO_2 production, NH_4-N, and NO_3-N were determined for six-inch soil samples collected before fumigation in 2016 and before planting, after emergence N application, and after harvest in 2017. Leaflet chlorophyll contents (SPAD readings) and petiole NO_3-N concentrations were measured at five times between hilling and harvest. The severity of *Verticillium* wilt was assessed from late July until September 12, nine days before harvest. Tuber yield, size, and quality (including the prevalence of scab) and vine and tuber N uptake were determined after harvest. Tuber sugar concentrations and French fry color were measured at harvest and after three months storage. Total and marketable yields were higher in the fumigated plots than in the non-fumigated plots, and yields were higher with Vapam than Chloropicrin. Yields increased with N rate regardless of fumigation. The percentage of yield represented by tubers weighing over six or ten ounces was higher and less responsive to N rate in fumigated plots than in non-fumigated plots, suggesting that fumigation may decrease N requirements for tuber bulking. Plots receiving Chloropicrin had a lower prevalence of scab than those receiving Vapam or no fumigant. Tuber specific gravity was higher in plots receiving Vapam than in non-fumigated plots, with Chloropicrin-treated plots intermediate. Soil respiration was lower in the fumigated plots than in the non-fumigated control plots after the fumigation treatments were applied, though this effect diminished over time. The fumigated plots, especially those treated with Chloropicrin, had high soil NH_4-N and low NO_3-N relative to the non-fumigated plots, indicating that fumigation may interfere with nitrification. Leaflet chlorophyll content increased with N application rate and was slightly higher in the plots receiving either fumigant than in the non-fumigated plots. Petiole NO_3-N concentrations also increased with N application rate, but while the fumigated plots had higher petiole NO_3-N concentrations initially, there was no significant effect of fumigation treatment on petiole NO_3-N concentration overall. Vine and tuber N concentrations increased with N application rate. Vine, tuber, and total N uptake also increased with N application rate, and N uptake was also higher in the treatments receiving either fumigant than the control plots. The non-fumigated control treatment had greater *Verticillium* wilt severity than the treatment receiving Chloropicrin, which had greater severity than the treatment receiving Vapam. Tuber glucose concentration decreased with increasing N application rate, but the effect of fumigation treatment on tuber glucose was ambiguous. The bud ends of tubers from the non-fumigated control treatment produced slightly darker French fries than those from the treatment receiving Vapam. Overall, we found that fumigation increased marketable yield at all N rates tested and decreased N requirements for tuber bulking, increased N uptake and leaf chlorophyll content, decreased *Verticillium* wilt severity, and decreased soil microbial activity, including nitrification, during the growing season.

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. The plots had been cropped to potatoes in a 3 to 4 year rotation for the previous 25 years, without fumigation.

Fumigation treatments were arranged in a randomized complete block design with four blocks and three fumigation treatments. The fumigation treatments were: no fumigation, with cultivation on October 24, 2016; cultivation on October 18, 2016, followed by fumigation with Chloropicrin on October 19, 2016 at 100 $lbs \cdot ac^{-1}$ applied in strips; and cultivation on October 24, 2016, followed by fumigation with Vapam at 70 $gal \cdot ac^{-1}$ injected at 6” and 10” on November 10.

Five N fertilization treatments were arranged as randomized 20 X 21-foot subplots within each fumigation plot, giving the study a split-plot randomized complete block design. 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.

A summary of the treatments is presented in Table 1.

Soil sampling

To assess initial soil characteristics in the study field, soil samples to a depth of six inches were collected on April 13 and sent to Agvise Laboratories (Benson, MN) to be analyzed for Bray P_2O_5; NH_4OAc-extractable K_2O, 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 2.

To evaluate responses of soil mineral N concentrations to treatment application, soil samples to a depth of six inches were collected from each plot on October 17, 2016, and April 13, July 5, and October 13, 2017. The samples were dried at 95°C for 48 hours, ground, and subsamples were extracted with 2N KCl. The extracts were analyzed for NH_4-N and NO_3-N concentrations using a Wescan nitrogen analyzer.

The soil microbial respiration rate was determined for a 40-g subsample of each sample using Solvita Soil CO_2 Burst Test kits (Woods End Laboratories), which measure the amount of CO_2 a wetted sample emits in a 24-hour period. The sample was placed a 150-mL plastic beaker inside a glass jar and wetted to achieve 50% water-filled pore space. A CO_2-detecting gel on a plastic paddle was placed inside the jar but outside the beaker, and the jar was sealed with a plastic lid with a CO_2-proof rubber gasket. The jars were incubated at 20°C for exactly 24 hours. The CO_2-detecting gel was immediately analyzed with a Solvita Digital Color Reader to measure the CO_2 concentration in the jar in ppm. A duplicate of one subsample, as well as a standard, were run with each set of Solvita tests to ensure accuracy.

Planting and N treatments

The subplots were planted with Russet Burbank whole "B" seed potatoes on April 25, 2017, 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 Chieftain cut "A" seed 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, 103 $lbs \cdot ac^{-1}$ P_2O_5, 182 $lbs \cdot ac^{-1}$ K_2O, 41 $lbs \cdot ac^{-1}$ S, 21 $lbs \cdot ac^{-1}$ Mg, 1.1 $lb \cdot ac^{-1}$ 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 (0-0-21.5-21S-10.5Mg), BluMin (17.5% S, 35.5% Zn), and Granubor (14.3% B). Environmentally Smart Nitrogen (ESN; 44-0-0; Agrium, Inc.) was hand-broadcast on subplots per the assigned N treatments shortly after shoot emergence, on May 11, and then hilled in.

Plant stand, leaflet chlorophyll content, and petiole NO_3-N

For each plot, plant stand in the harvest rows was recorded on June 8. The number of stems per plant for ten plants in the harvest rows was recorded on June 13.

On 5 days throughout the summer, chlorophyll content in the terminal leaflet of the fourth leaf from the tip of 20 shoots per plot was recorded with a Konica Minolta SPAD-502 chlorophyll meter, generating a single average SPAD reading for each plot. SPAD readings were taken on June 15 and 27, July 11 and 25, and August 8 (i.e., 35, 47, 61, 75, and 89 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.

Harvest, tuber quality, and tuber sugars and fry color

Tubers were harvested on September 21 (149 days after planting) and sorted by size and USDA grade. Representative 25-tuber samples were evaluated for hollow heart, brown center, dry matter content, and specific gravity. Representative 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 on a fresh-weight basis. Samples from the stem and bud ends were French-fried by USDA on October 10 and 11, and their reflectance was determined using a Photovolt reflectometer. Measurements of tuber sugar concentrations and reflectance were repeated three months later.

Data analysis

The data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the MIXED procedure. For each dependent variable related to tuber yield or quality or plant N uptake, fumigation treatment, N treatment, their interaction, and block were treated as fixed effects, while the interaction between block and fumigation treatment (the factor differentiating whole plots) was treated as a random effect. For repeatedly measured dependent variables, including soil respiration, soil NO_3-N, leaflet chlorophyll content, petiole NO_3-N concentration, and tuber sugar concentrations, dependent variables were analyzed as functions of sampling time, fumigation treatment, N treatment, their interactions, and block as fixed effects, block*fumigation treatment as a random effect, plot as the subject variable, and sampling time as the repeated-measures variable. An autoregressive (AR[1]) covariance matrix structure was used for chlorophyll content, petiole NO_3-N concentration, and tuber sugars, while a compound symmetrical (CS) structure was used for soil respiration and mineral N measurements, which were separated by significant events (the application of fumigation and N treatments and harvest) that were expected to minimize the effect of autocorrelation between sampling dates. In all models, denominator degrees of freedom were estimated using the Kenward-Roger approach (the KENWARDROGER option in SAS). Marginal means for dependent variables were determined using the LSMEANS statement, and post-hoc pairwise comparisons (alpha = 0.10) 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 0.10.

Results and discussion

Tuber yield, size, and grade

Tuber yield, size, and grade results are presented in Table 3. Total and marketable yield were related to both fumigation treatment and nitrogen application rate. The treatments receiving Vapam had higher yields than those receiving Chloropicrin, which had higher yields than the non-fumigated treatments, averaged across N application rates. Yields increased with increasing N application rate, especially between 40 and 180 $lbs \cdot ac^{-1}$ N total, averaged across fumigation treatments. The non-fumigated plots showed a stronger response to N rate than the plots receiving either fumigant, but the effect of the interaction between fumigation treatment and N application rate was not quite significant for either total or marketable yield.

The percentage of yield represented by tubers weighing over six ounces was lower in the non-fumigated plots than in those receiving Chloropicrin or Vapam, and a parallel but non-significant difference was observed for the percentage of yield represented by tubers over ten ounces. For both tuber-size thresholds, the percentage of yield in large tubers increased as the application rate of N increased, especially between 40 and 180 $lbs \cdot ac^{-1}$ N total. The non-fumigated control plots showed a much stronger response of the percentage of yield in tubers over six or ten ounces to N rate between 40 and 120 $lbs \cdot ac^{-1}$ N applied in total than did the plots receiving Chloropicrin or Vapam. As a result, the effect of the interaction between fumigation treatment and N rate was significant for both variables.

Tuber quality

Tuber quality results are presented in Table 4. The prevalence of hollow heart and brown center was higher in the subplots receiving 180 $lbs \cdot ac^{-1}$ N at total than those receiving other rates. The cause of this result is unclear.

The prevalence of scab was lower in the plots receiving Chloropicrin than in the non-fumigated plots or the plots receiving Vapam. The effect of the interaction between fumigation treatment and N application rate was significant at $\alpha = 0.10$, but this appears to be a reflection of the sporadic occurrence of scab, which was absent from 22 of 45 subplots, but present in up to 32% of tubers in others. 12 of the 23 subplots with scab were in the non-fumigated plots, versus 5 in Chloropicrin-treated plots and 7 in Vapam-treated plots, suggesting that both fumigants have some suppressive effect on scab.

Fumigation affected tuber specific gravity, with tubers from Vapam-treated plots having higher specific gravity than those from non-fumigated plots. Plots treated with Chloropicrin produced tubers with specific gravity intermediate between the non-fumigated and Vapam plots.

Soil respiration

The results of 24-hour CO_2 burst tests (a measure of soil microbial activity) are presented in Table 5. Fumigation treatment and the fumigation*date interaction were significantly related to soil CO_2 production. The non-fumigated control treatment had a higher rate of soil CO_2 production, averaged across N treatments, than either fumigated treatment in April and July 2017, but not in October 2016 (before the fumigation treatments were applied). The control treatment had a higher rate of soil CO_2 production than the Vapam treatment in October 2017, with the CO_2 production rate of the Chloropicrin treatment intermediate between the two and not significantly different from either.

The effect of the interaction between nitrogen treatment and date on soil CO_2 production was also significant. Three of the five nitrogen treatments showed decreases in CO_2 production between October 2016 and April 2017 and between July and October 2017, with increases in production between April and July 2017. The other two treatments did not follow this pattern. The treatment receiving no N at emergence had a steady decrease in soil CO_2 production across all four sampling times, and the treatment receiving 240 $lbs \cdot ac^{-1}$ N total had higher soil CO_2 production in October 2017 than in July of that year. The treatment receiving no N at emergence probably showed decreasing respiration throughout the study because N availability limited microbial activity. The high average CO_2 production in October 2017 of subplots receiving 240 $lbs \cdot ac^{-1}$ N total is difficult to explain.

Soil NH_4-N and NO_3-N

Soil NH_4-N and NO_3-N concentration results are presented in Table 6. Soil NH_4-N concentrations did not vary with treatment on October 17, 2016, before treatments were applied, nor on October 13, 2017, after harvest. Plots receiving Chloropicrin had higher soil NH_4-N concentrations than the non-fumigated control plots on both April 13 and July 5, 2017. Plots receiving Vapam had soil NH_4-N concentrations greater than the non-fumigated control plots but less than the plots fumigated with Chloropicrin on April 13, after fumigation but before N treatments applied at hilling. By July 5 (55 days after application of N treatments and hilling), the difference in soil NH_4-N concentration between the Vapam-treated plots and the non-fumigated plots was no longer significant.

Soil NO_3-N concentrations were unrelated to treatment on October 17, 2016, before treatments were applied. In all three samples taken after fumigation treatments were applied, the plots receiving Chloropicrin had lower soil NO_3-N concentrations than the non-fumigated plots. On July 5, 2017, the plots treated with Vapam had soil NO_3-N concentrations higher than the Chloropicrin-treated plots, but lower than the non-fumigated plots.

The high soil NH_4-N concentrations and low NO_3-N concentrations observed in the fumigated plots, particularly the Chloropicrin-treated plots, suggest that fumigation had an inhibitory effect on nitrification. Nitrification is mediated by microbes, and the inhibitory effect of fumigants on this process is presumably a result of the negative effect of fumigants on microbial activity. We observed similar effects on soil NH_4-N, but not NO_3-N, in 2016.

Soil NH_4-N concentration was only related to N application rate on July 5, 2017, after the N treatments were applied but before harvest. The subplots receiving no N at emergence had lower soil NH_4- N concentrations than those receiving between 140 and 260 $lbs \cdot ac^{-1}$ N, with the subplots receiving 80 $lbs \cdot ac^{-1}$ N intermediate. In contrast, soil NO_3-N increased with N application rate in both July and October 2017, though the relationship was stronger in July.

Plant stand and leaflet chlorophyll content

Results for plant stand and leaflet chlorophyll content are presented in Table 7. The number of stems per plant 33 days after the emergence fertilizer was applied was unrelated to treatment. However, plant stand was related to both fumigation treatment and the interaction between fumigation treatment and N treatment. The plots receiving Vapam had higher stand than those receiving Chloropicrin or no fumigant. The interaction effect is a result of the plots receiving Chloropicrin having higher stand than the non-fumigated plots among the subplots receiving 180 $lbs \cdot ac^{-1}$ N total; the non-fumigated plots had higher or equal stand to the plots receiving Chloropicrin at all other N application rates.

Chlorophyll content (based on readings from a Konica Minolta SPAD-502 chlorophyll meter) increased with N application rate on all five sampling dates. Chlorophyll content generally declined over time, while the response of chlorophyll content to N rate grew stronger over time. The non-fumigated control plots had slightly lower chlorophyll content than the plots receiving Chloropicrin or Vapam on each sampling date, resulting in a weak overall effect of fumigation treatment on chlorophyll content. There was a significant effect of the interaction between N treatment and sampling date. Chlorophyll content declined more rapidly over time in treatments receiving less N.

Petiole NO_3-N concentration

Results for petiole NO_3-N concentration are presented in Table 8. Petiole NO_3-N concentration generally decreased over time. Season-average petiole NO_3-N concentration increased with the application rate of N, but was not related to fumigation treatment or the interaction between fumigation treatment and N application rate.

While all N treatment showed rapid declines in petiole NO_3-N concentration at some point during the season, this decline occurred later in the season in treatments receiving higher rates of N. This resulted in a highly significant effect of the interaction between N application rate and sampling date on petiole NO_3-N concentration.

The effect of the interaction between fumigation treatment and sampling date was also significant. The treatments receiving no fumigation had a significantly lower mean petiole NO_3-N concentration (averaged across N application rates) on the first sampling date (June 15) than the treatments receiving either fumigant. On the third sampling date (July 11), the treatments receiving Vapam had a significantly higher mean petiole NO_3-N concentration than the treatments receiving either Chloropicrin or no fumigant. There was no significant difference in petiole NO_3-N concentration between any two fumigation treatments on any of the other three sampling dates.

Tissue N concentration and N uptake

Results for tissue N concentration and N uptake are presented in Table 9. Tissue N concentration increased with the application rate of N in both vines and tubers but did not respond to fumigation treatment. Tissue N uptake in both vines and tubers also increased with the application rate of N. In addition, the treatments fumigated with Chloropicrin or Vapam took up more N into both vines and tubers than the non-fumigated control plots. The results for total N uptake paralleled those for vines and tubers separately.

Verticillium wilt development

Results for the development of *Verticillium* wilt between July 31 and September 12 are presented in Table 10. The severity of *Verticillium* wilt increased between late July and mid-September, as expected. The non-fumigated control treatment had greater *Verticillium* wilt severity than either fumigated treatment on all four sampling dates, even though both fumigated treatments had severity close to 90% by September 12. The non-fumigated control treatment therefore had a greater relative area under the disease progression curve (RAUDPC) than either fumigated treatment. The difference in *Verticillium* severity between the two fumigated treatments was less pronounced, but the plots receiving Chloropicrin had greater severity on August 22 and 31, as well as a greater RAUDPC, than the plots receiving Vapam.

N application rate also affected *Verticillium* severity, with disease severity declining as N application rate increased.

Tuber sugars and French fry color

Tuber sugar and French fry reflectance results are presented in Tables 11 (glucose), 12 (sucrose), and 13 (reflectance). In both stem end and bud end tissues, glucose concentrations, averaged across sampling times, generally decreased as the application rate of N increased. Fumigation treatment was not related to glucose concentration in either end of the tuber, but the effect of the interaction between fumigation treatment and N application rate on stem-end glucose concentration was significant in both ends. In either tissue, this interaction effect is difficult to interpret.

In both the stem end and the bud end, sucrose concentrations generally decreased as the application rate of N increased. The average stem-end sucrose concentration at harvest of treatments fumigated with Chloropicrin was relatively low, resulting in a significant effect of the interaction between storage time and fumigation treatment. Similarly, sucrose concentration in the bud end was significantly related to the interaction between storage time and fumigation treatment because the mean sucrose concentration of non-fumigated treatments at harvest was relatively high. The effect of the interaction between fumigation treatment and N application rate on bud-end sucrose concentration was also significant. This effect is difficult to interpret.

French fries made from the stem ends of tubers receiving 40 $lbs \cdot ac^{-1}$ N in total were darker (i.e., had lower reflectance scores) than those made from tubers receiving N at higher rates. French fries made from the bud ends of tubers from the non-fumigated treatments were darker than fries made from Vapam-fumigated treatments, with the treatments fumigated with Chloropicrin intermediate.

Conclusions

Fumigation increased tuber yield and size relative to the non-fumigated control plots. While tuber yield and size increased with increasing N rate, fumigation lowered the N requirement for bulking. Fumigation with Vapam improved plant stand relative to the non-fumigated control, while fumigation with Chloropicrin did not, raising the possibility, that Vapam is more effective at controlling some pathogen that reduces stand. The two fumigated treatments had slightly higher leaflet chlorophyll contents than the non-fumigated control, as well as higher petiole NO_3-N concentrations early in the season and higher N uptake into both vines and tubers, indicating that fumigation improves the ability of plants to acquire N from the soil. Fumigation had no clear effect on tuber sugar content, though it slightly improved the color of French fries made from the bud end of the tuber. Overall, fumigation treatment appeared to affect soil N cycling processes and overall microbial activity negatively, but plants in fumigated plots had higher tuber yields, larger tubers, and greater ability to take up N than those in 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 2017.

Fumigation treatment (whole plots)	Nitrogen applicaton rate, $lbs \cdot ac^{-1}$ (subplots)	
	Emergence (ESN)[1]	Total[2]
Control	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 $lbs \cdot ac^{-1}$ N at planting as DAP (18-46-0)

Table 2. Initial soil characteristics in the study site at the Sand Plain Research Farm in Becker, MN, in 2017.

0 - 6 inches											
Primary macronutrients		Secondary macronutrients			Micronutrients					Other characteristics	
Bray P	K	SO4-S	Ca	Mg	Zn	Fe	Mn	Cu	B	Organic matter	pH
ppm										%	
37	118	2.5	940	160	2.1525	37.8	10.2	0.68	0.29	2.25	6.15

Table 3. 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 2017. Values within the same column that share a letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Treatment		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}									%	
Fumigation treatment	Control	16	80	140 b	92 b	56 b	384 c	284 c	84	368 c	73 b	36
	Chloropicrin	13	84	182 a	140 a	94 a	513 b	444 b	56	500 b	81 a	45
	Vapam	14	80	199 a	148 a	107 a	547 a	471 a	62	533 a	83 a	46
Fumigation (P-value)		0.3112	0.9232	**0.0083**	**0.0017**	*0.0521*	**0.0004**	**<0.0001**	0.1450	**0.0003**	**0.0168**	0.1151
Total N applied (lbs·ac^{-1})	40	15	117 a	184	73 b	23 d	412 c	350 c	46 d	396 c	65 c	21 d
	120	14	86 b	184	132 a	67 c	482 b	388 b	79 ab	468 b	78 b	40 c
	180	14	72 c	179	144 a	95 b	503 ab	407 ab	83 a	490 ab	83 a	48 b
	240	14	66 c	162	146 a	107 b	495 ab	420 a	61 cd	481 ab	83 a	50 ab
	300	15	67 c	158	139 a	135 a	515 a	433 a	67 bc	500 a	84 a	53 a
Nitrogen (P-value)		0.4286	**<0.0001**	0.1001	**<0.0001**	**<0.0001**	**<0.0001**	**0.0002**	**0.0022**	**<0.0001**	**<0.0001**	**<0.0001**
Control	40	19	121 a	123	15 g	2	281	228	34 f	262	48 e	6 e
	120	16	81 b	159	91 f	34	382	263	103 ab	366	74 d	33 d
	180	14	61 c	139	123 cde	68	406	268	123 a	391	81 abc	47 b
	240	16	70 bc	138	109 ef	68	400	303	81 bcd	384	78 bcd	44 bc
	300	15	68 bc	139	121 cdef	108	451	356	80 bcd	436	81 abc	50 ab
Chloropicrin	40	13	114 a	196	92 f	34	448	394	41 f	435	72 d	28 d
	120	13	105 a	199	125 cde	59	501	437	51 def	488	76 cd	36 cd
	180	13	75 bc	200	168 ab	92	547	465	70 cde	535	84 ab	48 b
	240	13	62 bc	159	165 ab	126	524	451	60 cdef	511	86 a	55 a
	300	15	64 bc	155	152 abc	158	545	473	57 cdef	530	86 a	57 a
Vapam	40	14	115 a	234	111 def	33	506	430	63 cdef	492	74 d	28 d
	120	13	70 bc	192	179 a	107	562	465	84 bc	549	85 a	51 ab
	180	14	78 bc	197	142 bcd	126	557	487	56 def	543	83 ab	48 ab
	240	13	67 bc	190	165 ab	128	562	505	44 ef	549	86 a	52 ab
	300	17	70 bc	179	145 bc	139	550	468	64 cdef	533	84 ab	52 ab
Fumigation*Nitrogen (P-value)		0.4759	*0.0867*	0.2048	**0.0292**	0.1598	0.1735	0.3119	**0.0104**	0.1238	**0.0003**	**0.0020**

Table 4. Effects of fumigation and N treatment on the prevalence of hollow heart, brown center, and scab; tuber dry matter content; and tuber specific gravity for Russet Burbank potatoes grown at the Sand Plain Research Farm in Becker, MN, in 2017. Values within the same column that share a letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Treatment		Tuber quality				
		Hollow heart (%)	Brown center (%)	Scab (%)	Dry matter content (%)	Specific gravity
Fumigation treatment	Control	4	4	7.2 a	20.6	1.0765 b
	Chloropicrin	3	3	1.6 b	21.2	1.0795 ab
	Vapam	2	2	5.5 a	21.1	1.0813 a
Fumigation (P-value)		0.4303	0.4303	**0.0238**	0.2296	*0.0568*
Total N applied (lbs·ac^{-1})	40	1 b	1 b	7.7	20.8	1.0781
	120	1 b	1 b	3.6	21.3	1.0805
	180	8 a	8 a	2.9	21.2	1.0822
	240	2 b	2 b	3.1	20.7	1.0758
	300	2 b	2 b	6.6	20.9	1.0789
Nitrogen (P-value)		**0.0049**	**0.0049**	0.2331	0.4898	0.1319
Control	40	3	3	13.0 ab	19.8	1.0725
	120	0	0	10.7 abc	21.4	1.0800
	180	11	11	1.9 de	21.1	1.0775
	240	6	6	5.8 bcde	20.1	1.0750
	300	0	0	4.6 cde	20.8	1.0775
Chloropicrin	40	1	1	1.4 de	21.4	1.0800
	120	0	0	0.0 e	21.3	1.0800
	180	8	8	1.7 de	21.4	1.0872
	240	1	1	3.6 cde	20.9	1.0708
	300	6	6	1.5 de	21.1	1.0798
Vapam	40	0	0	8.7 abcd	21.2	1.0819
	120	2	2	0.0 e	21.3	1.0815
	180	6	6	5.2 cde	21.3	1.0820
	240	0	0	0.0 e	21.0	1.0816
	300	0	0	13.8 a	20.6	1.0793
Fumigation*Nitrogen (P-value)		0.5176	0.5176	*0.0538*	0.8045	0.2487

Table 5. 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 Solvita CO_2 Burst Test kits, at the Sand Plain Research Farm in Becker, MN, in 2017. Values within the same column that share a lowercase letter and values within a row that share an uppercase letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, sampling date, or one of their interaction is less than 0.10.

Treatment		Solvita CO_2 burst test results (ppm increase in CO_2 after 24 hours incubation at 70°F)				
		October 17, 2016	April 13, 2017	July 5, 2017	October 13, 2017	Average across dates
Fumigation treatment	Control	50.7 -, AB	44.3 a, C	52.3 a, A	45.4 a, BC	48.2 a
	Chloropicrin	51.2 -, A	34.1 b, C	38.2 b, BC	41.9 ab, B	41.3 b
	Vapam	54.7 -, A	26.5 c, C	37.6 b, B	37.8 b, B	39.2 b
Fumigation (P-value)						**0.0099**
Fumigation*date (P-value)		**0.0013**				
Total N applied (lbs·ac^{-1})	40	51.6 ab, A	40.6 a, B	39.7 b, B	34.9 c, B	41.7 b
	120	50.8 ab, A	38.3 ab, B	51.7 a, A	44.6 ab, AB	46.4 a
	180	51.3 ab, A	35.0 abc, B	43.8 b, A	43.8 ab, A	43.5 ab
	240	58.6 a, A	31.4 bc, C	36.5 b, C	47.1 a, B	43.4 ab
	300	48.7 b, A	29.7 c, C	41.8 b, AB	38.1 bc, B	39.6 b
Nitrogen (P-value)						*0.0707*
Nitrogen*date (P-value)		**0.0290**				
Control	40	50.1	47.5	42.4	35.9	44.0
	120	49.9	55.8	62.5	47.5	53.9
	180	52.8	42.7	50.5	54.7	50.2
	240	49.1	42.2	54.2	52.3	49.5
	300	51.6	33.4	51.9	36.5	43.3
Chloropicrin	40	49.2	37.5	42.7	32.7	40.5
	120	43.6	32.5	52.5	42.7	42.8
	180	48.4	37.9	38.0	36.7	40.2
	240	66.9	29.3	23.1	52.3	42.9
	300	47.8	33.3	34.8	45.2	40.3
Vapam	40	55.4	36.9	33.9	36.0	40.5
	120	59.0	26.6	40.3	43.6	42.4
	180	52.6	24.2	42.9	40.0	39.9
	240	59.7	22.6	32.3	36.8	37.9
	300	46.8	22.3	38.7	32.7	35.1
Fumigation*nitrogen (P-value)						0.7140
Fumigation*nitrogen*date (P-value)		0.2506				
Average across treatments		52.2 A	35 C	42.7 B	41.7 B	
Date (P-value)		**<0.0001**				

Table 6. Effects of fumigation and N treatments on NH_4-N and NO_3-N concentrations in the top six inches of soil on October 17, 2016, and April 13, July 5, and October 13, 2017, in plots used to grow Russet Burbank potatoes at the Sand Plain Research Farm in Becker, MN, in 2017. Values within the same column that share a lowercase letter, and values within a row that share an uppercase letter, are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, sampling date, or one of their interactions is less than 0.10.

Treatment		NH_4-N ($mg \cdot kg^{-1}$ dry soil)					NO_3-N ($mg \cdot kg^{-1}$ dry soil)				
		October 17, 2016	April 13, 2017	July 5, 2017	October 13, 2017	Average across dates	October 17, 2016	April 13, 2017	July 5, 2017	October 13, 2017	Average across dates
Fumigation treatment	Control	2.6 -, B	1.0 c, B	8.4 b, A	0.8 -, B	3.2 b	1.7 -, D	5.1 a, C	7.4 a, A	6.1 a, B	5.1 a
	Chloropicrin	2.3 -, B	14.1 a, A	17.1 a, A	1.1 -, B	8.7 a	1.7 -, C	3.5 b, B	4.5 c, A	4.8 b, A	3.6 b
	Vapam	2.6 -, BC	5.9 b, AB	9.2 b, A	1.1 -, C	4.7 b	1.9 -, C	4.9 a, B	6.0 b, A	6.1 a, A	4.7 a
Fumigation (P-value)						**0.0278**					**<0.0001**
Fumigation*date (P-value)		**0.0008**					**0.0154**				
Total N applied ($lbs \cdot ac^{-1}$)	40	2.6 -, AB	6.3 -, A	0.5 c, B	1.7 -, AB	2.8 c	1.6 -, B	5.0 -, A	2.6 e, B	4.9 c, A	3.5 c
	120	2.6 -, B	8.0 -, A	4.5 c, AB	0.7 -, B	4.0 bc	1.6 -, C	4.1 -, AB	3.8 d, B	5.2 bc, A	3.7 c
	180	2.8 -, BC	6.7 -, B	14.2 b, A	0.9 -, C	6.1 ab	1.7 -, C	4.6 -, B	6.5 c, A	5.4 bc, AB	4.5 b
	240	2.1 -, BC	7.1 -, B	18.4 ab, A	0.8 -, C	7.1 a	2.3 -, D	4.3 -, C	7.7 b, A	6.0 ab, B	5.1 ab
	300	2.5 -, BC	7.1 -, B	20.2 a, A	0.9 -, C	7.7 a	1.6 -, D	4.5 -, C	9.4 a, A	6.9 a, B	5.6 a
Nitrogen (P-value)						**0.0011**					**<0.0001**
Nitrogen*date (P-value)		**<0.0001**					**<0.0001**				
Control	40	2.6	1.0	0.8	1.2	1.4	1.9	5.2	4.2	6.0	4.3
	120	2.3	1.2	1.8	0.3	1.4	1.6	4.4	4.7	6.1	4.2
	180	2.9	1.0	6.6	0.8	2.9	1.8	5.6	7.6	5.9	5.2
	240	1.7	1.2	16.0	0.8	4.9	1.8	4.4	9.0	5.4	5.1
	300	3.3	0.8	16.9	0.8	5.4	1.6	5.8	11.6	7.1	6.6
Chloropicrin	40	2.7	14.3	0.5	2.0	4.9	1.3	3.2	1.9	3.8	2.6
	120	2.1	15.2	8.5	0.7	6.6	2.0	3.6	3.2	3.6	3.1
	180	2.7	13.2	28.2	1.0	11.3	1.5	3.2	5.2	4.3	3.5
	240	2.0	13.8	23.5	0.9	10.1	2.0	4.1	5.8	5.8	4.4
	300	2.2	13.9	24.7	0.8	10.4	1.7	3.4	6.5	6.4	4.5
Vapam	40	2.6	3.4	0.1	1.8	2.0	1.6	6.6	1.6	4.8	3.6
	120	3.4	7.6	3.2	1.1	3.8	1.3	4.4	3.5	5.9	3.8
	180	2.7	6.0	7.7	0.9	4.3	1.9	4.9	6.6	6.0	4.9
	240	2.5	6.1	15.7	0.7	6.3	3.1	4.4	8.2	6.8	5.6
	300	2.1	6.5	19.1	1.2	7.2	1.4	4.2	10.0	7.2	5.7
Fumigation*nitrogen (P-value)						0.8530					0.8125
Fumigation*nitrogen*date (P-value)		0.9945					0.7569				
Average across treatments		2.5 C	7.0 B	11.6 A	1.0 C		1.8 C	4.5 B	6.0 A	5.7 A	
Date (P-value)		**<0.0001**					**<0.0001**				

Table 7. Effects of fumigation and N treatment on plant stand, stems per plant, and leaflet chlorophyll content (SPAD meter readings) on five dates in 2017 for Russet Burbank potatoes at the Sand Plain Research Farm in Becker, MN. Values within the same column that share a lowercase letter and values in the same row that share an uppercase letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, sampling date, or one of their interactions is less than 0.10.

Treatment		June 8 stand (%)	June 13 stems / plant	Leaflet chlorophyll content (SPAD meter readings)					
				June 15	June 27	July 11	July 25	August 8	Average across dates
Fumigation treatment	Control	87 b	2.3	43.9	41.4	37.6	35.6	32.8	38.3 b
	Chloropicrin	85 b	2.5	44.6	43.8	38.4	36.7	34.6	39.6 a
	Vapam	97 a	2.6	44.8	43.2	38.4	36.2	34.5	39.4 a
Fumigation (P-value)		**0.0061**	0.1277						*0.0817*
Fumigation*date (P-value)				0.1833					
Total N applied (lbs·ac^{-1})	40	88	2.5	44.0 b, A	40.2 b, B	33.7 d, C	29.3 d, D	23.0 e, E	34.0 e
	120	90	2.5	43.9 b, A	43.1 a, A	36.7 c, B	33.6 c, C	28.8 d, D	37.2 d
	180	90	2.5	44.3 ab, A	43.8 a, A	39.0 b, B	38.1 b, B	35.4 c, C	40.2 c
	240	89	2.4	44.8 ab, A	43.4 a, B	40.0 b, C	39.7 a, C	40.4 b, C	41.6 b
	300	91	2.4	45.1 a, A	43.7 a, B	41.3 a, D	40.2 a, E	42.3 a, C	42.5 a
Nitrogen (P-value)		0.5567	0.6946						**<0.0001**
Nitrogen*date (P-value)				**<0.0001**					
Control	40	86 efgh	2.3	43.2	38.7	33.2	28.7	22.3	33.2
	120	90 cdef	2.3	43.7	42.2	36.8	32.7	27.2	36.5
	180	83 gh	2.4	44.6	41.7	37.8	37.1	33.7	39.0
	240	88 efg	2.4	44.2	42.4	39.4	39.7	38.3	40.8
	300	88 efg	2.3	43.7	42.3	40.7	40.0	42.8	41.9
Chloropicrin	40	81 h	2.6	44.3	41.5	33.7	30.6	23.5	34.7
	120	85 fgh	2.7	43.9	44.1	36.8	33.7	28.9	37.5
	180	91 bcde	2.5	43.6	45.3	39.8	38.6	37.2	40.9
	240	81 h	2.4	44.7	43.9	40.5	40.4	40.9	42.1
	300	90 defg	2.3	46.4	44.2	41.3	40.5	42.6	43.0
Vapam	40	99 a	2.7	44.4	40.3	34.2	28.6	23.1	34.1
	120	96 abc	2.6	44.1	43.0	36.6	34.5	30.4	37.7
	180	97 ab	2.6	44.9	44.6	39.5	38.7	35.5	40.6
	240	97 ab	2.4	45.5	43.8	40.2	39.0	42.0	42.1
	300	95 abcd	2.5	45.2	44.6	41.7	40.2	41.6	42.7
Fumigation*Nitrogen (P-value)		**0.0169**	0.8592						0.9375
Fumigation*Nitrogen*date (P-value)				0.3913					
Average across treatments				44.4 A	42.8 B	38.1 C	36.2 D	34.0 E	
Date (P-value)				**<0.0001**					

Table 8. Effects of fumigation and N treatment on petiole NO_3-N concentrations on five dates in 2017 for Russet Burbank potatoes at the Sand Plain Research Farm in Becker, MN. Values within the same column that share a lowercase letter and values in the same row that share an uppercase letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, sampling date, or one of their interactions is less than 0.10.

Treatment		Petiole NO_3-N concentration ($mg \cdot kg^{-1}$)					
		June 15	June 27	July 11	July 25	August 8	Average across dates
Fumigation treatment	Control	16540 b, A	13316 -, B	7851 b, C	6065 -, D	3068 -, E	9368
	Chloropicrin	18730 a, A	13445 -, B	7346 b, C	6386 -, D	2166 -, E	9615
	Vapam	18669 a, A	12782 -, B	9649 a, C	6514 -, D	2142 -, E	9951
Fumigation (P-value)							0.3821
Fumigation*date (P-value)		**<0.0001**					
Total N applied ($lbs \cdot ac^{-1}$)	40	13464 d, A	2669 d, B	289 e, C	167 d, C	143 c, C	3347 e
	120	17740 c, A	12264 c, B	3236 d, C	852 d, D	259 c, D	6870 d
	180	18735 bc, A	15889 b, B	8213 c, C	4473 c, D	964 c, E	9655 c
	240	20036 a, A	17195 a, B	13037 b, C	10989 b, D	3982 b, E	13048 b
	300	19924 ab, A	17889 a, B	16635 a, C	15127 a, D	6945 a, E	15304 a
Nitrogen (P-value)							**<0.0001**
Nitrogen*date (P-value)		**<0.0001**					
Control	40	9289	1470	321	253	201	2307
	120	16566	12346	2334	482	266	6399
	180	17371	16275	7271	4287	1387	9318
	240	19428	18104	12766	10238	4972	13101
	300	20045	18387	16566	15065	8516	15716
Chloropicrin	40	16169	4386	235	116	74	4196
	120	17561	11399	3149	1145	366	6724
	180	19665	16109	7593	4534	662	9713
	240	20084	16860	9887	11230	2995	12211
	300	20172	18470	15868	14905	6733	15230
Vapam	40	14934	2152	312	131	155	3537
	120	19093	13047	4226	931	146	7489
	180	19168	15282	9776	4597	843	9933
	240	20596	16619	16459	11500	3979	13831
	300	19555	16809	17471	15411	5586	14967
Fumigation*Nitrogen (P-value)							0.1344
Fumigation*Nitrogen*date (P-value)		0.2900					
Average across treatments		17980 A	13181 B	8282 C	6322 D	2459 E	
Date (P-value)		**<0.0001**					

Table 9. Effects of fumigation and N treatment on vine and tuber N concentration and N uptake into vines, tubers, and vines and tubers combined, for Russet Burbank potatoes grown at the Sand Plain Research Farm in Becker, MN, in 2017. Values within the same column that share a letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, or their interaction is less than 0.10.

Treatment		Tissue N (% dry wt.)		N uptake (lbs·ac^{-1} N)		
		Vines	Tubers	Vines	Tubers	Total
Fumigation treatment	Control	1.34	1.34	17 b	108 b	125 b
	Chloropicrin	1.28	1.29	27 a	141 a	168 a
	Vapam	1.25	1.27	27 a	146 a	173 a
Fumigation (P-value)		0.5350	0.3079	**0.0039**	**<0.0001**	**<0.0001**
Total N applied (lbs·ac^{-1})	40	1.00 d	0.96 e	9 e	81 d	91 d
	120	0.95 d	1.16 d	14 d	119 c	133 c
	180	1.19 c	1.34 c	23 c	143 b	166 b
	240	1.39 b	1.44 b	29 b	147 b	176 b
	300	1.91 a	1.58 a	42 a	169 a	212 a
Nitrogen (P-value)		**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Control	40	1.13	1.04	6	58	64
	120	1.01	1.20	10	98	108
	180	1.22	1.37	16	117	133
	240	1.45	1.52	20	122	142
	300	1.88	1.55	34	146	179
Chloropicrin	40	0.94	1.01	11	97	108
	120	0.96	1.09	15	116	131
	180	1.14	1.41	24	165	189
	240	1.39	1.36	34	148	182
	300	1.98	1.58	48	180	229
Vapam	40	0.93	0.84	11	89	100
	120	0.89	1.20	16	143	159
	180	1.21	1.25	29	147	176
	240	1.34	1.45	33	171	204
	300	1.87	1.60	45	182	227
Fumigation*Nitrogen (P-value)		0.9579	0.1808	0.3792	0.2227	0.4068

Table 10. Severity (prevalence) of *Verticillium* wilt in Russet Burbank potatoes grown at the Sand Plain Research Farm in Becker, MN, 2017 under different fumigation treatments and N application rates. If two values within a column have a letter in common, they do not differ by more than the $LSD_{P = 0.05}$ value and are not significantly different from each other (P > 0.05).

Treatment		Wilt (% Severity)				AUDPC	RAUDPC
		7/31	8/22	8/31	9/12		
Fumigation treatment	Control	1.6 a	73.8 a	93.2 a	99.1 a	2733 a	0.635 a
	Chloropicrin	0.2 b	31.9 b	60.4 b	92.1 b	1682 b	0.391 b
	Vapam	0.1 b	21.3 c	47.0 c	88.1 b	1352 c	0.314 c
Fumigant $LSD_{P = 0.05}$		0.6	9.5	10.4	5.6	239	0.056
Total N applied ($lbs{\cdot}ac^{-1}$)	40	1.9 a	67.1 a	91.4 a	98.3 a	2610 a	0.607 a
	120	0.6 b	55.8 a	84.3 a	97.8 a	2343 a	0.545 a
	180	0.2 b	38.8 b	65.5 b	96.4 ab	1869 b	0.435 b
	240	0.3 b	33.3 b	54.9 bc	90.2 b	1637 b	0.381 b
	300	0.1 b	16.4 c	38.1 c	82.7 c	1151 c	0.268 c
Nitrogen $LSD_{P = 0.05}$		0.8	12.3	13.5	7.2	309	0.072
40	Control	5.0 a	93.8 a	99.3 a	100.0 a	3150 a	0.733 a
120		1.4 b	87.5 a	97.3 a	99.3 a	2988 ab	0.695 ab
180		0.5 b	76.3 ab	97.8 a	99.3 a	2809 ab	0.653 ab
240		0.6 b	77.5 ab	96.0 a	100.0 a	2816 ab	0.655 ab
300		0.3 b	33.8 d	75.5 ab	96.8 ab	1899 de	0.442 de
40	Chloropicrin	0.4 b	62.5 bc	91.3 a	98.5 a	2522 bc	0.587 bc
120		0.4 b	50.0 cd	83.0 ab	98.0 a	2239 cd	0.521 cd
180		0.1 b	22.5 ef	61.3 bc	97.0 ab	1575 e	0.366 e
240		0.1 b	13.8 ef	45.0 cd	85.5 bc	1200 f	0.279 f
300		0.0 b	10.5 ef	21.3 de	81.3 cd	873 fg	0.203 fg
40	Vapam	0.3 b	45.0 cd	83.8 ab	96.5 ab	2159 cd	0.502 cd
120		0.0 b	30.0 de	72.5 b	96.0 ab	1802 de	0.419 de
180		0.0 b	17.5 ef	37.5 cde	93.0 abc	1223 f	0.284 f
240		0.0 b	8.8 f	23.8 de	85.0 bc	895 fg	0.208 fg
300		0.0 b	5.0 f	17.5 e	70.0 d	681 g	0.158 g
$LSD_{P = 0.05}$		1.4	20.0	24.0	12.4	518	0.121

Table 11. Effects of fumigation, N treatment, and time in storage (0 or 3 months) on stem-end and bud-end tuber glucose concentrations of Russet Burbank potato plants grown at the Sand Plain Research Farm in Becker, MN, in 2017. Values within the same column that share a lowercase letter and values within the same row that share an uppercase letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, months in storage, sampling time, or one of their interactions is less than 0.10.

Treatment		Glucose (mg·g^{-1})					
		Stem end			Bud end		
		0 months	3 months	Average	0 months	3 months	Average
Fumigation treatment	Control	2.599	3.356	2.977	0.578	0.461	0.520
	Chloropicrin	2.635	3.160	2.898	0.544	0.454	0.499
	Vapam	2.422	3.352	2.887	0.547	0.443	0.495
Fumigation (P-value)				0.7096			0.8285
Fumigation*date (P-value)		0.1938			0.9285		
Total N applied (lbs·ac^{-1})	40	3.664	4.266	3.965 a	0.661	0.589	0.625 a
	120	2.618	3.461	3.039 b	0.593	0.572	0.582 ab
	180	2.316	3.134	2.725 c	0.506	0.382	0.444 cd
	240	2.046	2.822	2.434 d	0.410	0.348	0.379 d
	300	2.115	2.764	2.439 d	0.614	0.374	0.494 bc
Nitrogen (P-value)				**<0.0001**			**0.0003**
Nitrogen*date (P-value)		0.8887			0.1586		
Control	40	3.222	4.050	3.636 bc	0.639	0.782	0.711 a
	120	2.794	3.876	3.335 c	0.485	0.429	0.457 bcdefg
	180	2.282	3.046	2.664 ef	0.619	0.428	0.524 bcde
	240	2.104	2.749	2.426 ef	0.538	0.400	0.469 bcdef
	300	2.592	3.060	2.826 de	0.611	0.268	0.439 cdefg
Chloropicrin	40	3.776	3.851	3.814 b	0.647	0.551	0.599 abc
	120	3.042	3.426	3.234 cd	0.605	0.529	0.567 abcd
	180	2.400	3.167	2.784 e	0.400	0.295	0.347 fg
	240	2.013	2.778	2.395 ef	0.336	0.407	0.371 efg
	300	1.943	2.578	2.260 f	0.735	0.489	0.612 ab
Vapam	40	3.994	4.896	4.445 a	0.697	0.435	0.566 abcd
	120	2.016	3.082	2.549 ef	0.688	0.757	0.723 a
	180	2.267	3.189	2.728 e	0.498	0.422	0.460 bcdef
	240	2.022	2.939	2.480 ef	0.355	0.237	0.296 g
	300	1.811	2.653	2.232 f	0.495	0.365	0.430 defg
Fumigation*Nitrogen (P-value)				**0.0052**			**0.0193**
Fumigation*Nitrogen*date (P-value)		0.8767			0.1389		
Average across treatments		2.5518 B	3.2892 A		0.5565 A	0.4528 B	
Date (P-value)		**<0.0001**			**0.0006**		

Table 12. Effects of fumigation, N treatment, and time in storage (0 or 3 months) on stem-end and bud-end tuber sucrose concentrations of Russet Burbank potato plants grown at the Sand Plain Research Farm in Becker, MN, in 2017. Values within the same column that share a lowercase letter and values within the same row that share an uppercase letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, months in storage, sampling time, or one of their interactions is less than 0.10.

Treatment		Sucrose ($mg \cdot g^{-1}$)					
		Stem end			Bud end		
		0 months	3 months	Average	0 months	3 months	Average
Fumigation treatment	Control	0.514 a, -	0.478 -, -	0.496 a	1.324 a, A	1.095 -, B	1.210 a
	Chloropicrin	0.381 b, B	0.471 -, A	0.426 b	1.133 b, -	1.092 -, -	1.112 b
	Vapam	0.476 a, -	0.479 -, -	0.477 a	1.096 b, -	1.082 -, -	1.089 b
Fumigation (P-value)				**0.0101**			**0.0012**
Fumigation*date (P-value)		**0.0112**			**0.0047**		
Total N applied ($lbs \cdot ac^{-1}$)	40	0.536	0.525	0.530 a	1.285	1.167	1.226 a
	120	0.531	0.540	0.535 a	1.150	1.097	1.124 bc
	180	0.456	0.453	0.455 b	1.208	1.081	1.145 b
	240	0.370	0.444	0.407 b	1.167	1.068	1.117 bc
	300	0.392	0.419	0.406 b	1.111	1.036	1.074 c
Nitrogen (P-value)				**<0.0001**			**0.0121**
Nitrogen*date (P-value)		0.5099			0.9065		
Control	40	0.600	0.508	0.554	1.321	1.102	1.211 abc
	120	0.650	0.581	0.615	1.399	1.198	1.298 a
	180	0.463	0.433	0.448	1.279	1.085	1.182 abcde
	240	0.406	0.445	0.426	1.360	1.040	1.200 abcd
	300	0.451	0.425	0.438	1.262	1.051	1.157 bcdef
Chloropicrin	40	0.443	0.560	0.501	1.305	1.168	1.237 ab
	120	0.418	0.469	0.443	1.096	1.086	1.091 defg
	180	0.382	0.407	0.395	1.107	1.074	1.090 efg
	240	0.311	0.516	0.413	1.072	1.122	1.097 cdefg
	300	0.353	0.404	0.378	1.083	1.010	1.046 fg
Vapam	40	0.565	0.507	0.536	1.229	1.230	1.229 ab
	120	0.526	0.569	0.548	0.956	1.007	0.981 g
	180	0.523	0.519	0.521	1.239	1.084	1.161 bcdef
	240	0.392	0.372	0.382	1.069	1.042	1.055 fg
	300	0.373	0.429	0.401	0.988	1.048	1.018 g
Fumigation*Nitrogen (P-value)				0.2351			*0.0897*
Fumigation*Nitrogen*date (P-value)		0.6314			0.8110		
Average across treatments		0.4569	0.4761		1.184 A	1.09 B	
Date (P-value)		0.2551			**0.0012**		

Table 13. Effects of fumigation, N treatment, and time in storage (0 or 3 months) on the reflectance (lightness of color) of French fries made from the stem ends and bud ends of Russet Burbank tubers grown at the Sand Plain Research Farm in Becker, MN, in 2017. Values within the same column that share a lowercase letter and values within the same row that share an uppercase letter are not significantly different from each other (i.e. P > 0.10). Letters are only included where the P-value of the effect of fumigation, N treatment, months in storage, sampling time, or one of their interactions is less than 0.10.

Treatment		Reflectance					
		Stem end			Bud end		
		0 months	3 months	Average	0 months	3 months	Average
Fumigation treatment	Control	23.7	24.1	23.9	40.4	39.9	40.1 b
	Chloropicrin	25.0	24.5	24.8	40.7	40.7	40.7 ab
	Vapam	24.6	24.3	24.5	41.6	41.1	41.3 a
Fumigation (P-value)				0.1860			*0.0578*
Fumigation*date (P-value)		0.6619			0.9007		
Total N applied (lbs·ac^{-1})	40	22.8	23.3	23.0 b	40.3	40.8	40.5
	120	24.5	24.6	24.6 a	40.5	40.0	40.2
	180	24.9	24.5	24.7 a	41.6	40.4	41.0
	240	25.3	24.5	24.9 a	41.8	41.3	41.6
	300	24.7	24.5	24.6 a	40.2	40.3	40.2
Nitrogen (P-value)				**0.0358**			0.1826
Nitrogen*date (P-value)		0.8748			0.7913		
Control	40	23.3	22.7	23.0	40.5	38.8	39.6
	120	24.3	23.3	23.8	40.3	40.3	40.3
	180	24.0	25.0	24.5	39.0	39.0	39.0
	240	24.0	24.1	24.1	40.8	40.4	40.6
	300	22.8	25.1	23.9	41.3	40.9	41.1
Chloropicrin	40	21.0	22.7	21.9	40.5	40.2	40.3
	120	24.3	25.9	25.1	39.0	40.2	39.6
	180	25.8	24.9	25.3	43.3	41.6	42.4
	240	26.3	23.9	25.1	41.3	42.2	41.7
	300	27.6	25.2	26.4	39.5	39.2	39.4
Vapam	40	24.0	24.4	24.2	39.8	43.3	41.5
	120	25.0	24.6	24.8	42.3	39.5	40.9
	180	25.0	23.7	24.4	42.5	40.7	41.6
	240	25.5	25.3	25.4	43.5	41.3	42.4
	300	23.7	23.3	23.5	39.8	40.7	40.2
Fumigation*Nitrogen (P-value)				0.1716			0.1114
Fumigation*Nitrogen*date (P-value)		0.4146			0.2848		
Average across treatments		24.4	24.3		40.9	40.5	
Date (P-value)		0.7490			0.4833		