Yield and Quality Responses of Ivory Russet and Russet Burbank Potatoes to P Rate, Banded P Application, Soil Fumigation, and Mycorrhizal Inoculation in High-P Soils

Executive Three-Year Summary

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Phosphorus (P) is a macronutrient that is essential for all forms of life. A deficiency of P in potatoes is associated with delayed vegetative growth, poor tuber set and bulking, and reduced yields. Excess P seldom affects plant growth, but it can increase eutrophication if it moves offsite into surface water. Phosphorus management is therefore an important consideration from both production and environmental standpoints.

Phosphorus fertilizer recommendations for potatoes are based on soil test P and yield goal, but numerous studies have shown that economic responses can sometimes occur even on high P testing soils. For this reason, some P fertilizer is usually recommended for potatoes even when soil test P is high. However, a P response is not always guaranteed even on lower P testing soils.
Phosphorus in soil exists in both inorganic and organic forms. It is considered a very immobile soil nutrient with availability of inorganic forms primarily controlled by soil pH. In acid soils, P binds tightly to soil particles by forming insoluble iron and aluminum compounds and in alkaline soils it forms insoluble calcium compounds. The optimal soil pH for P availability is generally between 6 and 7. Placement of P fertilizer in a band near the root system is one way of increasing P availability.

The reasons why potatoes often respond to phosphorus even under high soil P conditions are not entirely known but could be related to several factors. For example, potatoes naturally have a limited root system and the practice of hilling limits that root system even further. Because P is immobile in soil, plant roots depend on an increased root surface area to increase the probability of intercepting soil P in areas that have not yet been depleted. As plant roots take up P, the amount available for further uptake decreases and therefore growing into areas of higher soil P is an important adaptation to increase P supply to the plant.

Soil pH may also be a factor that limits P uptake. As discussed above, fixation by iron and aluminum in acid soils and calcium in alkaline soils reduces P availability. For some varieties soils are maintained at a pH below 5.5 to control common scab. While this practice can improve tuber quality, it may also result in lower P availability. Another reason for variable P response may be due to soil borne diseases such as verticillium and pathogenic nematodes, which can further limit root growth. To control soil borne diseases fumigation is used but this practice is not specific to disease organisms and may also reduce beneficial microbes such as mycorrhizae. Mycorrhizae are naturally occurring symbiotic fungi that form a symbiotic relationship with plant roots to increase root surface area and therefore improve phosphorus uptake. Finally, there could be distinct varietal differences in P uptake due to differences in root structure and surface area. In addition, some varieties may be more efficient in P acquisition and uptake than others due to root adaptations to solubilize fixed P or breakdown organic P.

Objectives

To explore some of these factors in more detail, a three-year experiment was conducted at the Sand Plain Research Farm in Becker, Minnesota with an overall goal of improving predictability of potato response to P fertilizer. Specific objectives were to 1) compare P response of two potato varieties in fumigated and non-fumigated soils, 2) determine the effect of mycorrhizal inoculation on P response, and 3) evaluate broadcast vs. banding of P fertilizer on tuber yields.

Methods

The soil at the experimental sites had a pH that ranged from 6.4 to 6.9 and a Bray P soil test that ranged from 95 to 146 ppm. The pH was in the range for optimum P availability and soil test P was in the very high range indicating the probability of P response to applied fertilizer for most crops would be low. Treatments for this study included, with and without fumigation, two varieties, Russet Burbank and Ivory Russet, and nine P treatments replicated 4 times for a total of 144 plots. The nine P treatments were: 0, 75 150, 300 and 450 lbs P_2O_5/A as triple super phosphate broadcast applied and incorporated in the spring before planting; mycorrhizae inoculation without P fertilizer and with 150 lbs P_2O_5 broadcast applied; banded P fertilizer at 75 and 150 lb P_2O_5/A. Fumigated plots received 40 gallons/A of Vapam the first year and 50/A gallons the second year. MycoGold was used as the mycorrhizae inoculant and applied at the labeled rate in furrow at planting. The experiment was set up the first year in two separate areas – one fumigated and the other not fumigated as a split plot design with variety as the main plot and P treatment as the subplot. The second and third years the experiment was set up as a split-split plot treatment arrangement with fumigation as the main plot, variety as the subplot and P treatment at the sub-sub plot. Because of the change in experimental design, the first year had to be analyzed separately from the 2nd and 3rd years.

Results

<u>P Rate and Fumigation Response</u>: Total yield increased with increasing P rate in all three years of the study for Ivory Russet under both fumigated and nonfumigated conditions. In contrast, the P response for Russet Burbank in the first year of the study was not significant (Fig 1c). However, in the second year of the study, yields of both varieties increased with an increasing P rate in both fumigated and nonfumigated conditions. At equivalent P rates, yields for both varieties were higher under fumigated conditions than nonfumigated conditions. In the third year of the study both varieties responded to P fertilizer under fumigated conditions but only marginally under non-fumigated conditions. An overall P response curve averaged over varieties in fumigated and non fumigated conditions over all three years is provided in Figure 1.

<u>Mycorrhizae inoculation</u>: Over the three years of the study, mycorrhizal inoculation had no effect on yield of either variety when applied at planting at 0 and 150 lb P_2O_5/A under nonfumigated or fumigated conditions. These results suggest that the P response in these soils is not related to lack of mycorrhizal associations.

<u>Banding vs. broadcast applied P</u>: Mixed effects were found for P placement over the three years. In the first year, banding at equivalent rates to broadcast had no effect on yields for Russet Burbank in either fumigated on non-fumigated conditions. There was an unexpected decrease in Ivory

Russet yields when banding was used under fumigated conditions and no effect of placement under non-fumigated conditions (data not presented). In the second and third years of the study, results were more consistent with banded P applications tending to increase yields of both varieties when compared to broadcast applications at equivalent P rates.

Phosphorus fertilizer economics: Phosphorus fertilizer prices have increased over the past three years with a peak cost of $1.02/lb P_2O_5. The yield increase of 0.127 cwt would be required to pay for each extra lb of P_2O_5 applied assuming a potato value of $8.00/cwt. Based on a cost analysis for the second year of the study, adding P fertilizer at peak prices would only have been cost effective when potatoes were grown under fumigated conditions. This suggests that root growth under non-fumigated conditions was not sufficient to take advantage of the extra P fertilizer applied when P fertilizer costs are high and would result in a loss. If the cost of P fertilizer decreased to pre-2020 levels, P fertilizer addition would be cost effective. These results suggest that under fumigated conditions it is important to optimize other inputs to realize the full effect of fumigation.

Summary and Conclusions

The reason why potatoes sometimes respond to P fertilizer in high P testing soils continues to be puzzling. However, based on this research, it is unlikely due to lack of mycorrhizal associations. Ivory Russet was more responsive to P the first year of the study than Russet Burbank, but both varieties responded to P fertilizer the second and third years. Phosphorus response was observed under both fumigated and nonfumigated conditions but there seemed to be a greater response to P when fumigation was used. Banding was effective in two of the three years and may reduce the need for higher P application rates. While potatoes can respond to P fertilizer in high P testing soils, yield increases may not be sufficient to offset the cost of P fertilizer when fertilizer prices are high, especially if soilborne diseases are prevalent. Further research is needed to determine if new potato varieties can be developed that can more efficiently take up and utilize P at lower soil test P levels.

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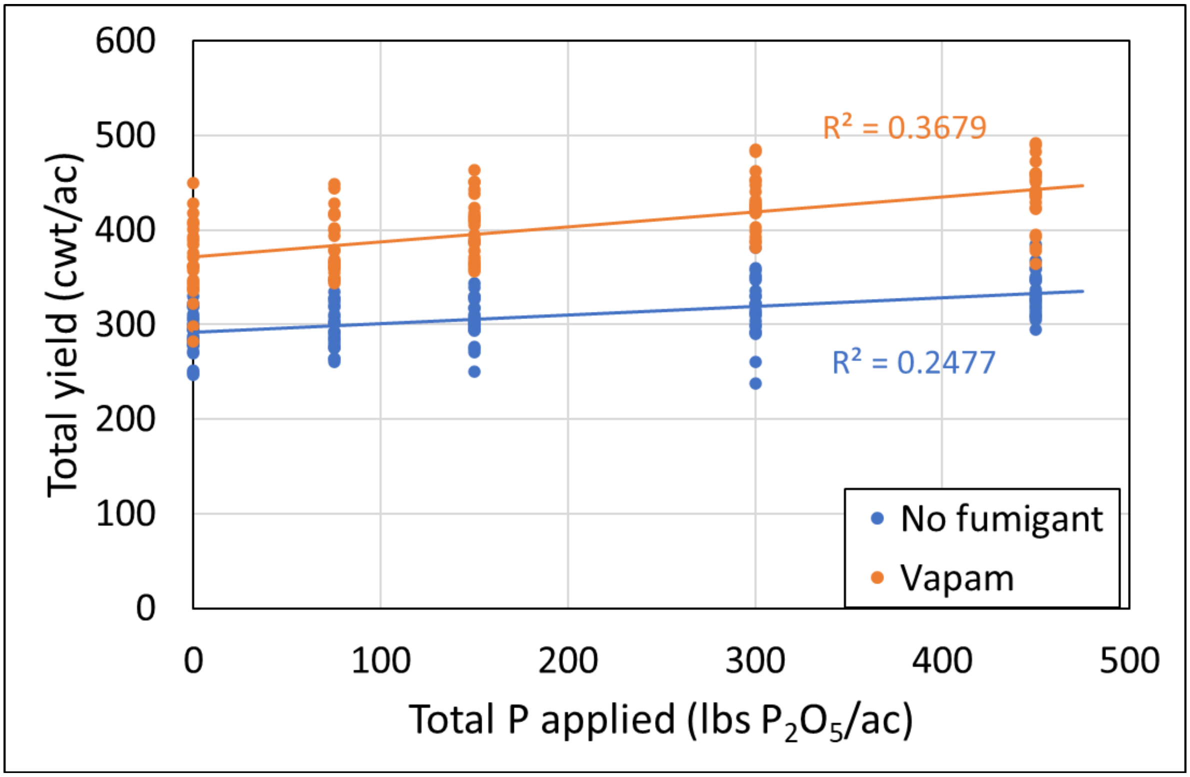
Figure 1. Effect of P fertilizer application on total yields under fumigated and non-fumigated conditions averaged over varieties and years.



Yield and quality responses of Ivory Russet and Russet Burbank potatoes to P rate, banded P application, soil fumigation, and mycorrhizal inoculation in high-P soils: year three

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Summary

Potato yield often increases with phosphorus (P) fertilizer application even under high soil-test P conditions, suggesting that potato plants do not take up P efficiently. This may be because potato plants have limited root systems or because they are not efficient at forming mycorrhizal associations, possibly as a side effect of soil fumigants used to control soilborne pathogens. If the limited spread of potato plant root systems limits P uptake, plants receiving a banded application of P should respond as if they had received a broadcast application at a higher rate. If the ability to form mycorrhizae limits P uptake, plants inoculated with mycorrhizal fungi at planting should respond as if they had received P at a higher rate. In addition, if potato plants are able to form mycorrhizae with native soil fungi, and if populations of these fungi are suppressed by soil fumigation, then (1) plants grown in plots fumigated with metam sodium should respond positively to P fertilization at higher rates than plants grown in unfumigated plots because more P is required to maximize yield and (2) plants in fumigated plots should respond more positively to inoculation with mycorrhizal fungi at planting than plants in unfumigated plots. Root system reach, ability to form mycorrhizae, and P use efficiency all potentially vary among cultivars. We conducted an experiment to assess the roles soil fumigation, fertilizer placement, inoculation with mycorrhizal fungi, and potato cultivar play in determining P use efficiency. We used a split-split-plot randomized complete block design with four replicates. Whole plots were defined by fumigation treatment (no fumigant or fall-applied metam sodium) and subplots by cultivar (Ivory Russet or Russet Burbank). Sub-subplots were defined by nine P treatments: five in which P was broadcast-applied as triple super phosphate (TSP) at different rates (0, 75, 150, 300, or 450 lbs/ac P_2O_5), two in which the mycorrhizal product MycoGold Liquid was applied in-furrow at planting and P was broadcast at 0 or 150 lbs/ac P_2O_5, and two in which P was banded at planting at 75 or 150 lbs/ac P_2O_5. Initial soil P concentration in the field was 128-146 ppm Bray and 223-238 ppm Mehlich-3, with a P saturation index (PSI; Mehlich-3 P : Mehlich-3 Al) of 21.4-23.0%. Soil fumigation with metam sodium was effective in reducing the number of *Verticillium* propagules per gram of soil (VPPG). In unfumigated plots, VPPG was higher in subplots with Russet Burbank than Ivory Russet. Total, marketable, and U.S. No. 1 yield increased with P rate in both cultivars, but only in plots fumigated with metam sodium. The yield response to P treatment did not differ significantly between the two cultivars, except that U.S. No. 2 yield decreased with increasing P rate in Russet Burbank and increased with increasing P rate in Ivory Russet. The percentage of Ivory Russet yield in tubers over 6 or 10 ounces increased with P rate, but this was not true of Russet Burbank, suggesting that the yield response of Ivory Russet was due to tuber size while that of Russet Burbank was due to tuber number. Tuber specific gravity increased with P rate and was higher in fumigated plots and in Ivory Russet. Contrary to what would be expected if the availability of mycorrhizal partners limits potato plant P use efficiency, the responses of tuber yield, size, and specific gravity to P rate did not depend on whether the soil was fumigated with metam sodium, nor did applying a mycorrhizal product improve these metrics.

Background

Potato yield often increases in response to phosphorus (P) fertilizer application even at high soil-test P. This is especially true in acidic, irrigated soils, where yield responses have been observed at Bray P concentrations of up to 150 ppm. This suggest that potato plants do not take up soil P efficiently. This inefficiency may have two causes, both related to the low mobility of available P in the soil. First, potato plant root systems are not extensive, with few roots extending more than two feet into the soil, limiting the area over which they can access soil P. This issue could be addressed through banded rather than broadcast application of P fertilizer, placing more of the P applied within range of the plants' root systems.

Second, potato plants in agricultural systems may lack mycorrhizal associations, which would improve the plant's ability to access what P is available within reach of their root systems. The lack of mycorrhizae, in turn, may occur because the soil lacks mycorrhizal fungi or because potato plants are inefficient at forming mycorrhizae efficiently even when potential partners are available. In either case, applying mycorrhizal fungi to the soil can be expected to improve P uptake efficiency and tuber yield. Consistent with this expectation, previous studies have found that inoculation with arbuscular mycorrhizal fungi can improve potato plant vigor and yield. Both the extensiveness of potato plant root systems and their efficiency at forming mycorrhizae are likely to depend on plant genetics. Thus, different cultivars of potato plants may be expected to differ in their abilities to exploit available P in the soil and in their responsiveness to banded P application and inoculation of seed with mycorrhizal fungi. Our previous research at the Sand Plain Research Farm in Becker, MN, has indicated that the cultivars Russet Burbank and Ivory Russet have different responses to the application rate of P.

If efficiency in forming mycorrhizal associations limits P uptake in potato plants, soil fumigation might be expected to decrease P use efficiency, if it decreases native populations of mycorrhizal fungi. This effect might be masked by the overall positive effects of fumigation on plant health through the suppression of soil borne pathogens, but its presence may be indicated by a stronger response (e.g., in terms of yield or P uptake) to inoculation with mycorrhizal fungi in fumigated soils than in unfumigated soils.

Bray P concentration does not account for the potential for soluble aluminum (Al) in the soil to fix available P, making it no longer available for plants. This issue tends to become more significant at lower soil pH, as Al becomes more soluble at low pH. Research in Eastern Canada has found that a P saturation index (PSI: Melich-3 P / Melich-3 Al * 100) may be a better indicator of the potential for plants to respond to P fertilization in lower pH soils. The researchers suggest threshold PSI values (19.2% where pH < 5.5 and 14.2% where pH > 5.5) above which P fertilization should be limited to crop requirements in order to reduce P fixation.

The objectives of this study, which is in its third year, are to evaluate how potato yield responses to P rate are affected by (1) cultivar, (2) soil fumigation with metam sodium, (3) applying MycoGold Liquid (MycoGold LLC), a mycorrhizal product, in-furrow at planting, and (4) banded versus broadcast application of P fertilizer. These results will be considered in the context of the site's PSI, Bray P, and Mehlich-3 P.

Methods

Study design

The study was conducted at the Sand Plain Research Farm in 2022 on a Hubbard loamy sand soil. The previous crop was soybeans. A split-split plot randomized complete block design was deployed, with whole plots defined by fumigation treatment, subplots by potato cultivar, and sub-subplots by P application treatment. The fumigation treatments were (1) no fumigation and (2) fumigation with metam sodium the fall before planting. The cultivars used were Russet Burbank and Ivory Russet. The nine P treatments were as follows: (1) a check treatment receiving no P; four treatments receiving (2) 75, (3) 150, (4) 300, or (5) 450 lbs/ac P_2O_5 as triple super phosphate (TSP; 0-45-0-15Ca) broadcast before planting; two treatments inoculated in-furrow with the mycorrhizal product MycoGold Liquid at planting and receiving either (6) zero or (7) 150 lbs/ac P_2O_5 as TSP broadcast before planting; and two treatments receiving either (8) 75 or (9) 150 lbs/ac P_2O_5 as TSP banded at planting. A summary of the P treatments is presented in Table 1.

Soil tests

Soil samples to a depth of six inches were taken from each whole plot in each block on April 22, 2022. These samples were analyzed for Bray P; Melich-3 P, Al, Ca, Mg, Mn, Fe, Zn, and Cu; pH; loss-on-ignition organic matter content; ammonium-acetate-extractable K; hot-water-extractable B; and calcium-phosphate-extractable SO_4^{2-}-S. Samples to a depth of two feet were collected at the same time. These were analyzed for NH_4^+-N and NO_3^--N using a Wescan Nitrogen Analyzer. Results are presented in Table 2.

On July 13, a second set of six-inch soil samples was collected from each half of the field (blocks 1 and 2 in one half and blocks 3 and 4 in the other) and each combination of fumigation treatment and cultivar. These samples were sent fresh to Allied Cooperative (Plainfield, WI) and analyzed for *Verticillium* propagules and root lesion nematodes.

Treatment applications

Metam sodium was shank-injected into the soil in the appropriate plots at a rate of 50 gal/ac on October 20, 2021. The field was irrigated immediately after fumigant application.

On April 25, 2022, 200 lbs/ac MOP (0-0-60) and 200 lbs/ac SulPoMag (0-0-22-21S-11Mg) were broadcast applied to the entire field, providing 164 lbs/ac K_2O equivalent, 42 lbs/ac S, and 22 lbs/ac Mg. TSP was broadcast applied by hand to treatments 2 through 5 and 7. The field was cultivated on April 26 to incorporate the fertilizer.

A mixture of whole and cut 3-ounce seed tubers were planted by hand on May 3 (blocks 1 and 2) and 4 (blocks 3 and 4). Rows were spaced 36 inches apart and tubers were paced twelve inches apart within rows. Each sub-subplot comprised four, 20-foot rows, in which the central 18 feet of the middle two rows were eventually used for harvest samples. Each block was surrounded by a three-foot buffer of additional tubers to reduce field edge effects. After all tubers were placed on each planting day, MycoGold Liquid was applied in-furrow per the manufacturer's directions to treatments 6 and 7. Rows were closed by machine on the day they were planted. TSP was mechanically banded in treatments 8 and 9 at this time. In addition, a blend of 87 lbs/ac urea (46-0-0), 233 lbs/ac MOP, 191 lbs/ac SulPoMag, 2.8 lbs/ac $ZnSO_4$ (35.5% Zn, 17.5% S), and 3.3 lbs/ac Boron 15 (15% B) was banded into all rows, supplying 40 lbs/ac N, 180 lbs/ac K_2O, 40 lbs/ac S, 21 lbs/ac Mg, 1 lb/ac Zn, and 0.5 lbs/ac B.

Belay was applied in-furrow for beetle control, along with the systemic fungicide Quadris, and the rows were closed by machine. Weeds, diseases, and insects were controlled using standard practices. Rainfall was supplemented with sprinkler irrigation using the checkbook method of irrigation scheduling. Rainfall and irrigation amounts are presented in Figure 1.

All treatments received 150 lbs/ac N as ESN (44-0-0, Nutrien, Ltd.) and 60 lbs/ac N as urea mechanically side dressed and then hilled in on May 23, so that 250 lbs/ac N were applied in total.

Petiole sampling

Petioles were collected from each sub-subplot on June 23 and July 7 and 21. The petiole of the fourth mature leaf from the shoot tip was collected from 30 leaves per plot. Petioles were dried at 140°F until their weight was stable and then ground. The ground samples were sent to Agvise Laboratories (Benson, MN) and analyzed for NO_3^--N using a FIALab Fialyzer 1000 Nitrate Analyzer and for P concentration by inductively coupled plasma-mass spectrometry.

Harvest

Vines were chopped with a flail mower on September 15. Tubers were machine-harvested from the central 18 feet of the middle two rows of each plot on September 22. These harvest samples were sorted and graded by machine between September 26 and October 3. A 25-tuber subsample was taken from each harvest sample and assessed for hollow heart, brown center, common scab, specific gravity, and dry matter content. End-of-season soil samples to a depth of 6 inches were collected from each sub-subplot on October 7 to be analyzed for pH and Melich-3 Al and P.

Statistical analyses

Analyses were performed using SAS 9.4 software. Response variables were analyzed as functions of fumigation treatment, cultivar, P treatment, their interactions, block, fumigant*block (whole plot), and fumigant*cultivar*block (subplot), all as fixed effects, using the GLIMMIX procedure. When the effects of fumigation, cultivar, P treatment, or their interactions were significant ($P \leq 0.10$), pairwise comparisons were evaluated using Fisher's LSD using the DIFF option in the LSMEANS statement of the model. Values were considered significantly different if $P \leq 0.10$. Five comparisons among treatments were made using CONTRAST statements. Treatments 1 – 5 were compared in (1) a check-versus-P comparison and (2) linear and (3) quadratic contrasts on the application rate of P; (4) treatments 1 and 3 were compared with treatments 6 and 7 to evaluate the effect of adding mycorrhizae; and (5) treatments 2 and 3 were compared with treatments 8 and 9 to evaluate the effect of broadcast versus banded P application.

Results

Soil Verticillium propagules and root lesion nematodes

Results for soil *Verticillium* propagule population density and root lesion nematode abundance are presented in Table 3. Root lesion nematodes were not detected in any subplot. *Verticillium* propagule density was higher in unfumigated plots than in plots fumigated with metam sodium. Among unfumigated plots, but not the fumigated plots, propagule concentrations were higher in Russet Burbank subplots than Ivory Russet subplots.

Tuber yield

Results for tuber yield are presented in Table 4.

Overall, total and marketable yields, yields of U.S. No. 1 tubers, and the percentages of total yield in tubers over 6 and 10 ounces were higher in plots to which metam sodium had been applied than in unfumigated plots.

Russet Burbank had higher total, U.S. No. 1, U.S. No. 2, and total marketable yield than Ivory Russet, while Ivory Russet had higher percentages of its total yield in tubers over 6 and 10 ounces than Russet Burbank.

The effect of the interaction between fumigation treatment and cultivar on tuber yield and size was significant. While both cultivars showed positive yield responses to metam sodium application, the effect was much more pronounced in Russet Burbank than in Ivory Russet. Russet Burbank also showed a positive response to fumigation in the percentage of total yield represented by tubers over six or ten ounces, while Ivory Russet showed no response of tuber size distribution to fumigation treatment.

Tuber yield and size also responded to P treatment. Based on contrasts, total yield, the yield of U.S No. 1 tubers, and marketable yield increased linearly with the application rate of P.

Yields tended to be lower, overall, in treatments receiving MycoGold Liquid (treatments 6 and 7) than in similar treatments receiving no supplemental mycorrhizae (treatments 1 and 3). Based on pairwise comparisons, this difference was only significant when no P was applied (treatment 1 vs. 6). Based on contrasts, total yield was marginally significantly higher in treatments with banded P application (treatments 8 and 9) than corresponding treatments with broadcast P application (treatments 2 and 3), but the difference was not significant in pairwise comparisons.

The percentage of yield in tubers over ten ounces increased linearly with the application rate of P. This relationship was weaker, but still present, for the percentage of yield in tubers over six ounces. Percentages of yield in tubers over six and ten ounces were significantly lower in treatments receiving mycorrhizae (treatments 6 and 7) than in similar treatments receiving no supplemental mycorrhizae (treatments 1 and 3), but in pairwise comparisons, these differences were only significant when no P fertilizer was applied (treatment 1 vs. 6).

The effect of the interaction between fumigation treatment and P treatment was significant for total yield, marketable yield (Figure 2), and the yield of U.S. No. 1 tubers. In plots fumigated with metam sodium, yields in sub-subplots that received P at rates of 300 or 450 lbs/ac P_2O_5 (treatments 4 and 5) were significantly higher than yields at lower P rates (treatments 1-3). In contrast, P rate had no significant effect on yield in non-fumigated plots. In unfumigated plots, the treatments receiving MycoGold Liquid (treatments 6 & 7) had significantly lower yields than corresponding treatments that did not receive this product (treatments 1 & 3). In plots fumigated with metam sodium, a similar, non-significant trend was seen between the treatments receiving no P fertilizer (treatment 1 vs. 6), but this trend was reversed with P applied at 150 lbs P2O5/ac (treatment 3 vs. 7).

The interaction between cultivar and P treatment was significantly related to the yield of U.S. No. 2 tubers and the percentage of yield represented by tubers over six or ten ounces. The yield of U.S. No. 2 tubers in Russet Burbank generally decreased with P rate across all treatments, while U.S. No. 2 yield in Ivory Russet tended to increase with P rate. The percentage of yield in tubers over six or ten ounces did not show a clear relationship to P rate, application method, or the use of MycoGold Liquid in Russet Burbank, while these percentages increased with P rate and decreased with the use of MycoGold Liquid in Ivory Russet.

The percentages of yield represented by tubers over six or ten ounces were related to the three-way interaction among fumigation treatment, cultivar, and P treatment. This may reflect a stronger negative response to the use of MycoGold Liquid (treatments 6 & 7 compared to 1 & 3) in unfumigated Ivory Russet subplots compared to the other combinations of fumigation treatment and cultivar.

Tuber quality

Hollow heart and brown center strongly tended to co-occur (Table 5). The prevalence of both conditions was significantly related to fumigation treatment, cultivar, and their interaction. Russet Burbank had a much higher prevalence of both conditions than Ivory Russet in both fumigation treatments, and metam sodium fumigation tended to suppress both conditions in both cultivars. Since the prevalence was so much higher in Russet Burbank, the effect of fumigation on prevalence was also much stronger in this cultivar, being statistically non-significant in Ivory Russet. The prevalence of hollow heart and brown center was also related to the interaction among fumigation treatment, cultivar, and P treatment. In Russet Burbank, among treatments that received neither MycoGold nor banded P (treatments 1-5), prevalence was highest in the absence of P fertilizer in unfumigated plots, but prevalence was highest at the highest P rate in plots fumigated with metam sodium. With the same cultivar, between the two treatments receiving mycorrhizae at planting (treatments 6 and 7), fumigation decreased the prevalence of hollow heart and brown center in the absence of P fertilizer (treatment 6), but not in its presence (treatment 7). In contrast, Ivory Russet showed little effect of fumigation treatment or P treatment on the prevalence of these defects, which was low in all cases.

Ivory Russet tubers showed a significantly higher prevalence of common scab than Russet Burbank tubers, though the condition was uncommon in both cultivars. Among Ivory Russet subplots, the prevalence of common scab was also marginally significantly related to P treatment. Based on contrasts, common scab was more prevalent in the banded treatments (treatments 8 and 9) than in the corresponding broadcast treatments (treatments 2 and 3). It was also less prevalent in treatments receiving broadcast P without MycoGold (treatments 2-5) than in the treatment receiving no P fertilizer or MycoGold (treatment 1).

Tuber specific gravity was higher in Russet Burbank subplots fumigated with metam sodium than in unfumigated subplots, but fumigation treatment had no effect on specific gravity in Ivory Russet. Overall, Ivory Russet had higher tuber specific gravity than Russet Burbank. As a result, the effects of fumigation treatment, cultivar, and their interaction on specific gravity were all significant. The effect of P treatment on tuber specific gravity was also significant, with specific gravity increasing linearly with the application rate of P.

Russet Burbank tuber dry matter content, like specific gravity, was higher in plots fumigated with metam sodium than in unfumigated plots. Dry matter content in Ivory Russet showed the opposite trend, resulting in a significant effect of the fumigant*cultivar interaction. Like specific gravity, dry matter content was higher in Ivory Russet than in Russet Burbank. The main effect of P treatment on dry matter content was not significant, but there was a significant effect of the fumigant*P treatment interaction, as well as the three-way interaction among cultivar, fumigation treatment, and P treatment. Both cultivars had higher dry matter contents in fumigated plots than unfumigated plots when P was broadcast-applied at 300 or 450 lbs/ac P_2O_5 (treatments 4 and 5), but lower dry matter in fumigated plots than unfumigated plots at 75 or 150 lbs/ac P_2O_5 (treatments 2 or 3). When no P was applied, regardless of whether MycoGold was applied (treatments 1 and 6), Russet Burbank had higher dry matter content in fumigated plots than unfumigated plots, while the opposite was true of Ivory Russet.

Tuber specific gravity is used as a proxy metric of tuber dry matter content, and the two variables were positively related in a linear regression treating each sub-subplot as an independent unit ($R^2 = 0.3466$).

Discussion

Consistent with the results of our research in previous seasons, total and marketable tuber yield and the yield of U.S. No. 1 tubers, averaged across the two cultivars, increased with the application rate of P within the range of rates evaluated (0 to 450 lbs/ac P_2O_5). This occurred despite the high Bray P and Melich-3 P concentrations (128-146 $mg \cdot kg^{-1}$and 223-238 $mg \cdot kg^{-1}$, respectively) at this site and the high PSI (21.4-23.0%). For comparison, an application rate of 75 lbs/ac P_2O_5 is expected to maximize yield when Bray P exceeds 51 ppm, and it is recommended that only enough P be applied to replace crop uptake (about 45 lbs/ac) when PSI exceeds 14.2% in soils with pH over 5.5.

Our previous research, including the results of this study in 2020, suggested that Ivory Russet might be more sensitive to P treatment than Russet Burbank. In 2022, however, the responses of total, marketable, and U.S. No. 1 yield to P treatment did not differ significantly between the two cultivars. The yield of U.S. No. 2 tubers was sensitive to P treatment in both cultivars, but in opposite directions, with Russet Burbank U.S. No. 2 tuber yield tending to decrease and Ivory Russet No. 2 yield tending to increase with increasing P rate. In terms of the percentage of yield represented by tubers over 10 ounces, tuber size in Ivory Russet responded positively to P rate while tuber size in Russet Burbank was not related to P rate. The fact that both cultivars showed a positive total and marketable yield response to P rate while only Ivory Russet showed a tuber size response suggests that Russet Burbank responded to higher P rates by producing more tubers while Ivory Russet responded by producing bigger tubers.

If potato plants are inefficient at taking up P because their root systems are not extensive, limiting the volume of soil in which they can access P, tuber yield would be expected to be higher with banded application than with broadcast application at the same rate. Although there was a tendency for total yield to be higher with banded P application than broadcast application, the difference was not significant in pairwise comparisons. This contrasts with results from 2021 where banded P fertilizer at equivalent rates resulted in higher yields than broadcast applications.

If a lack of mycorrhizae limited the ability of potato plants to access soil P, two patterns would be expected as a result. First, responses to P fertilizer rate should extend to higher P rates in fumigated plots than in unfumigated plots because less P fertilizer should be required to meet plant P requirements if plants are exploiting P more efficiently via native mycorrhizal fungi. Second, applying MycoGold should increase plants' access to available P more effectively in fumigated plots than in unfumigated plots, where native mycorrhizal fungi should be more abundant. Thus, yield responses to MycoGold application should be more positive in plots fumigated with metam sodium than in unfumigated plots. In this field and this year, total and marketable yield were highest at the highest two P rates (300 and 450 lbs/ac P_2O_5) in plots fumigated with metam sodium, but did not respond to P rate in unfumigated plots. This is consistent with the hypothesis that low infection with mycorrhizal fungi limits P use efficiency in fumigated soils. However, it could also indicate that endogenous soil P was sufficient to achieve the maximum yield in unfumigated plots because that maximum was low. Yields in unfumigated plots may have been limited by something other than P availability, such as soilborne pathogen loads. Contrary to expectations, marketable yield was more responsive to the application of MycoGold in unfumigated plots than in fumigated plots, and, at least in the absence of P fertilizer, the yield response to MycoGold was negative. Thus, the effects of mycorrhizal inoculation are unclear.

In terms of both tuber yield and tuber size distribution, Russet Burbank showed a stronger positive response to fumigation with metam sodium than Ivory Russet did (with Ivory Russet showing no significant tuber size response to fumigation treatment). This difference in the yield response to fumigation treatment may reflect the higher midseason abundances of *Verticillium dahliae* propagules in unfumigated Russet Burbank subplots compared to unfumigated Ivory Russet subplots, or it may indicate that potato early dying has a greater impact on Russet Burbank yield, due to that cultivar's longer growing season, than Ivory Russet yield.

P availability and application rate have been found in previous research to potentially limit tuber dry matter content and specific gravity. P fertilization with TSP has also been found to decrease the prevalence and severity of common scab. However, P availability and P fertilization appear to have little effect on the prevalence of hollow heart or brown center.

In this study in 2022, P treatment had little net effect on the prevalence of hollow heart and brown center. However, in Russet Burbank, the prevalence of hollow heart tended to decrease with increasing P rate in plots fumigated with metam sodium, while the relationship was reversed in unfumigated plots. This was not observed in the previous two years of this study, and it is not clear whether these apparently contrasting responses to P rate are biologically meaningful.

The prevalence of common scab was lower in Russet Burbank than Ivory Russet, while soil fumigation had no effect on scab prevalence. Common scab prevalence also appeared to be promoted by banded application of P. We found mixed evidence that fertilization with TSP decreased the prevalence of common scab. On one hand, the mean prevalence of common scab among treatments receiving broadcast-applied P without MycoGold was lower than that of the treatment receiving neither P nor MycoGold. On the other hand, among treatments receiving P, there was no tendency for the prevalence of common scab to decrease as the application rate of P increased.

As expected, tuber specific gravity increased with P rate, whether P was broadcast or banded and whether or not MycoGold was applied. Specific gravity was also higher in fumigated plots than unfumigated plots and in subplots with Ivory Russet than in subplots containing Russet Burbank. The specific gravity response to P treatment was not influenced by soil fumigation or potato cultivar.

Ivory Russet tubers had higher dry matter content than Russet Burbank tubers. Russet Burbank tuber dry matter content was higher in fumigated plots than in unfumigated ones, but dry matter was not related to fumigation treatment in Ivory Russet. Overall, dry matter responded differently to P treatment within each fumigation treatment, but there was no clear pattern to how fumigation affected the P response. It is not clear why dry matter, unlike specific gravity, did not show the expected positive response to P rate, though the two metrics were positively related in this study.

Overall, tuber yield (total, marketable, and U.S. No. 1), size, and specific gravity all responded positively to P rate in this study, primarily when fumigation was used. Response to P rate was less evident under nonfumigated conditions. Russet Burbank appeared to produce this positive yield response through higher tuber set, while Ivory Russet did so more through increased tuber size. The P response of specific gravity did not depend on cultivar. Contrary to our expectations if the availability of mycorrhizal partners limits potato plant P use efficiency, the responses of tuber yield, size, and specific gravity to P rate did not depend on whether the soil was fumigated with metam sodium, nor did applying a mycorrhizal product improve these metrics.

Table 1. The nine phosphorus (P) treatments applied to Russet Burbank and Ivory Russet potatoes in unfumigated and metam-sodium-fumigated plots at the Sand Plain Research Farm in 2022.

Treatment			
Number	P rate (lbs/ac)	Application	Mycorrhizae?[1]
1	0	NA	No
2	75	Broadcast	No
3	150	Broadcast	No
4	300	Broadcast	No
5	450	Broadcast	No
6	0	NA	Yes
7	150	Broadcast	Yes
8	75	Banded	No
9	150	Banded	No

[1]Applied in-furrow at planting with a hand sprayer

Table 2. Initial soil characteristics in the study field.

	0 - 6 inches															0 - 2 feet
Fumigation treatment	Bray P (mg/kg)	Melich-3 P (mg/kg)	Melich-3 Al (mg/kg)	PSI (%)	pH	Organic matter (%)	NH_4OAc-K (mg/kg)	Mehlich-3 Ca (mg/kg)	Mehlich-3 Mg (mg/kg)	Mehlich-3 Mn (mg/kg)	Mehlich-3 Fe (mg/kg)	Mehlich-3 Zn (mg/kg)	Mehlich-3 Cu (mg/kg)	Hot water B (mg/kg)	SO_4^{2-}-S (mg/kg)	NO_3^--N (mg/kg)
Control	128	223	1038	21.4	6.5	2.4	269	1852	350	66	168	8.0	2.4	0.4	11	0.4
Metam sodium	146	238	1033	23.0	6.4	2.1	218	1617	302	59	165	6.6	2.2	0.4	20	

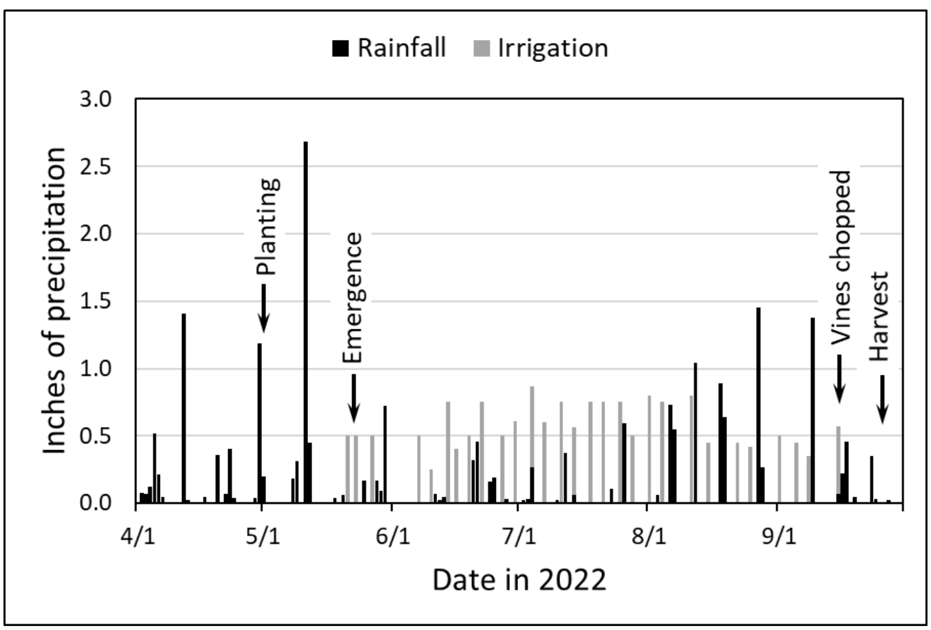

Figure 1. Inches of rainfall and irrigation in the study field in 2022. Irrigation amounts were determined by the checkbook method of irrigation scheduling. Monthly rainfall totals were as follows: April, 4.63

inches; May, 5.08 inches; June, 1.32 inches; July, 1.48 inches; August, 5.64 inches; September, 2.58 inches. Irrigation started on May 21 and ended on September 15. Monthly total irrigation amounts were as follows: May, 1.50 inches; June, 4.25 inches; July, 5.20 inches; August, 3.67 inches; September, 1.80 inches.

Table 3. Abundances of *Verticillium* propagules and root lesion nematodes in the soils of unfumigated plots and plots fumigated with metam sodium, in subplots with either Ivory Russet or Russet Burbank plants.

Fumigant	Cultivar	*Verticillium* propagules / g soil	Root lesion nematodes / 100 cc soil
None	Ivory Russet	16 b	0
	Russet Burbank	33 a	0
Metam sodium	Ivory Russet	7 b	0
	Russet Burbank	8 b	0
ANOVA effects (P-values)	Fumigant	**0.0467**	-
	Cultivar	0.1419	-
	Fumigant*cultivar	0.5133	-

Table 4. Effects of fumigation treatment, cultivar, and P treatment on tuber yield, size, and grade. Within each main effect, values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the main effect the value pertains to (fumigation treatment, cultivar, or P treatment) is significant (P<0.10).

Treatment description						Yield (CWT·ac^{-1})										% yield in tubers over:	
Fumigant	Cultivar	P treatment	P_2O_5 rate	Application	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total	US No. 1	US No. 2	Marketable	6 oz.	10 oz
None	Averaged	Averaged				5.0 a	54	46 b	73 b	53 b	38 b	269 b	175 b	35	210 b	62 b	35 b
Metam sodium						3.6 b	54	50 a	85 a	69 a	50 a	311 a	216 a	27	253 a	66 a	38 a
Averaged	Russet Burbank	Averaged				7.7 a	78 a	61 a	91 a	64 a	40 b	341 a	214 a	42 a	256 a	56 b	30 b
	Ivory Russet					0.8 b	30 b	35 b	67 b	58 b	48 a	238 b	177 b	31 b	207 b	72 a	43 a
Averaged	Averaged	1	0	NA	No	5.9 ab	49	47	77 b	56 bc	43 cde	278 c	182 cd	42	223 c	64 bc	36 bcd
		2	75	Broadcast	No	3.5 c	49	44	76 b	61 b	44 bcd	278 c	190 bc	35	225 c	67 ab	39 ab
		3	150	Broadcast	No	4.8 abc	55	50	79 ab	61 b	45 bcd	295 abc	204 ab	31	234 bc	64 bc	37 bcd
		4	300	Broadcast	No	3.4 c	53	49	81 ab	62 b	52 ab	300 ab	210 ab	34	244 ab	66 ab	39 ab
		5	450	Broadcast	No	4.1 abc	54	43	80 ab	72 a	58 a	311 a	219 a	34	253 a	68 a	42 a
		6	0	NA	Yes	3.2 c	57	49	67 c	49 c	32 f	258 d	162 d	35	197 d	56 d	30 e
		7	150	Broadcast	Yes	3.9 bc	57	52	81 ab	60 b	35 ef	288 bc	192 bc	35	227 c	62 c	33 de
		8	75	Banded	No	3.5 c	56	48	84 ab	64 ab	39 def	294 abc	195 bc	39	235 bc	63 bc	34 cd
		9	150	Banded	No	6.2 a	55	48	86 a	63 b	48 bc	306 a	203 ab	42	245 ab	66 ab	38 bc
ANOVA effects					Fumigant	**0.0295**	0.6936	**0.0077**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.4385	**<0.0001**	**<0.0001**	**0.0050**
					Cultivar	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0183**	**0.0028**	**<0.0001**	**<0.0001**	**0.0002**	**<0.0001**	**<0.0001**	**<0.0001**
					Fumigant*cultivar	*0.0800*	0.9104	0.7370	*0.0648*	**0.0002**	**<0.0001**	**<0.0001**	**0.0071**	**0.0005**	**<0.0001**	**<0.0001**	**<0.0001**
					P treatment	0.2102	0.3052	0.1650	**0.0238**	**0.0213**	**<0.0001**	**0.0002**	**0.0012**	0.6415	**0.0003**	**<0.0001**	**<0.0001**
					Fumigant*P treatment	0.6692	0.3608	0.3962	**0.0272**	0.6522	**0.0045**	*0.0892*	**0.0176**	0.3370	**0.0364**	0.1207	*0.0897*
					Cultivar*P treatment	*0.0956*	0.2645	**0.0241**	0.3001	0.4272	**0.0001**	0.4844	0.7628	**0.0288**	0.4276	**0.0029**	**<0.0001**
					Fumigant*cultivar*P treatment	0.6210	**0.0341**	0.3749	0.4840	**0.0368**	**0.0202**	0.0965	*0.0641*	0.1593	*0.0535*	**0.0011**	**0.0012**
Contrasts					P addition (1 v 2 - 5)	*0.0650*	0.1891	0.8197	0.6123	*0.0770*	0.1045	**0.0420**	**0.0139**	0.1023	*0.0677*	0.1545	**0.0498**
					Linear P rate (1 - 5)	0.2644	0.1451	0.4694	0.3863	**0.0064**	**0.0006**	**0.0005**	**0.0010**	0.3929	**0.0014**	*0.0809*	**0.0086**
					Quadratic P rate (1 - 5)	0.2626	0.4407	*0.0756*	0.7169	0.5362	0.5573	0.8077	0.4525	0.2008	0.9180	0.5801	0.6570
					Mycorrhizae (1&3 v 6&7)	*0.0625*	*0.0826*	0.4456	0.2589	0.2846	**0.0073**	*0.0910*	*0.0713*	0.8268	**0.0336**	**0.0004**	**0.0056**
					Broadcast v band (2&3 v 8&9)	0.4614	0.2625	0.6229	**0.0276**	0.5466	0.8522	*0.0748*	0.7744	*0.0741*	0.1794	0.7850	0.2867

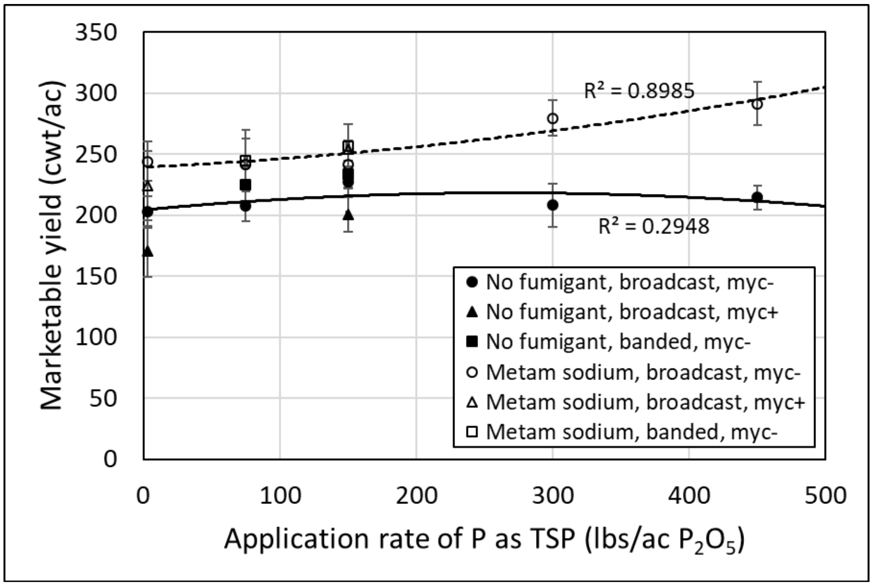

Figure 2. Marketable yield (mean ± S.E.) in each fumigation treatment, averaged between cultivars, as a function of the application rate of P. Curves are fitted on P treatments in which TSP was broadcast and MycoGold Liquid was not applied (treatments 1 – 5; solid circular markers).

Table 5. Effects of fumigation treatment, cultivar, and P treatment on tuber hollow heart, brown center, scab, specific gravity, and dry matter content. Within each main effect, values within a column that have a letter in common are not significantly different from each other in post-hoc pairwise comparisons. Letters are only presented when the main effect the value pertains to (fumigation treatment, cultivar, or P treatment) is significant (P<0.10).

Treatment description			Percent of tubers			Specific gravity	Dry matter (%)
Fumigant	Cultivar	P treatment	Hollow heart	Brown center	Scab		
None	Average of both	Average of all	12 a	11 a	2.1	1.0727 b	20.0
Metam sodium			8 b	8 b	1.8	1.0738 a	20.1
Average of both	Russet Burbank	Average of all	19 a	18 a	0.7 b	1.0702 b	19.2 b
	Ivory Russet		1 b	1 b	3.3 a	1.0763 a	20.8 a
Average of both	Average of both	1: 0 lbs/ac, myc -	13	13	3.8 a	1.0715 d	20.3
		2: 75 lbs/ac broad myc -	9	9	0.0 d	1.0713 d	19.7
		3: 150 lbs/ac broad myc -	10	10	0.8 cd	1.0740 abc	20.2
		4: 300 lbs/ac broad myc -	9	8	1.8 abcd	1.0753 a	20.3
		5: 450 lbs/ac broad myc -	13	13	3.5 ab	1.0751 a	20.2
		6: 0 lbs/ac, myc +	10	10	1.9 abcd	1.0718 d	19.6
		7: 150 lbs/ac broad myc +	10	9	2.0 abcd	1.0731 bcd	19.5
		8: 75 lbs/ac band myc -	10	9	1.5 bcd	1.0726 cd	20.2
		9: 150 lbs/ac band myc -	9	8	2.8 abc	1.0747 ab	20.2
ANOVA effects		Fumigant	**0.0033**	**0.0051**	0.5938	**0.0430**	0.5040
		Cultivar	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
		Fumigant*cultivar	**0.0245**	**0.0250**	0.4421	**0.0151**	**0.0033**
		P treatment	0.6493	0.5155	***0.0617***	**0.0013**	0.1600
		Fumigant*P treatment	0.4849	0.5977	0.7703	0.7652	**0.0311**
		Cultivar*P treatment	0.8935	0.8868	**0.0349**	0.1912	0.4979
		Fumigant*cultivar*P treatment	0.1544	0.1487	0.6613	0.8659	***0.0568***
Contrasts on P treatment		P addition (1 v 2 - 5)	0.1826	0.1874	**0.0231**	**0.0112**	0.4933
		Linear P rate (1 - 5)	0.8896	0.7928	0.3253	**<0.0001**	0.5700
		Quadratic P rate (1 - 5)	***0.0590***	**0.0322**	**0.0040**	0.1462	0.7833
		Mycorrhizae (1&3 v 6&7)	0.4357	0.3721	0.7246	0.7440	**0.0105**
		Broadcast v band (2&3 v 8&9)	0.7806	0.7365	**0.0448**	0.2162	0.2890