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 two

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Summary

Potato yield often responds positively to phosphorus (P) fertilizer even in soils with high soil-test P, suggesting that potatoes are not efficient at taking up P. This may be attributable to their short root systems or poor formation of mycorrhizal associations, possibly as a side effect of soil fumigation to control soilborne pathogens. Banded placement of P should place more P within reach of plant root systems, while inoculating seed with mycorrhizae may increase the number of mycorrhizae formed. 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 Vapam) and subplots by cultivar (Ivory Russet or Russet Burbank). Sub-subplots were defined by nine P treatments: five in which P was broadcast-applied at different rates (0, 75, 150, 300, or 450 lbs·ac^{-1} 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^{-1} P_2O_5, and two in which P was banded at 75 or 150 lbs·ac^{-1} P_2O_5. Total and marketable yield were higher in fumigated plots than unfumigated control plots, and this effect was stronger in Russet Burbank than Ivory Russet. Russet Burbank had higher total and marketable yield than Ivory Russet overall. Yield increased linearly with P rate in both cultivars, and the slope of this relationship was not significantly different between the two cultivars. Marketable yield showed a stronger response to P rate in fumigated plots than unfumigated control plots. Banded application resulted in higher yield than broadcast application at the same P rates for both cultivars. The percentage of yield represented by tubers over six ounces was higher in Ivory Russet in fumigated soils than in other combinations of fumigation treatment and cultivar, but it was not related to P treatment. Applying MycoGold at planting resulted in decreased yield of U.S. No. 2 tubers and increased prevalence of common scab. In Russet Burbank, hollow heart and brown center were more prevalent in fumigated plots than unfumigated plots overall. The effect of fumigation on these defects varied among P treatments but was not consistently related to P rate, use of MycoGold, or application method. In Ivory Russet, common scab was more common in unfumigated control plots than Vapam-fumigated plots overall, but the effect of fumigation on scab varied among P treatments in a way that was unrelated to P rate, MycoGold application, or P application method. Tuber specific gravity and dry matter content increased with P rate, and this increase was greater in fumigated plots than unfumigated control plots. In end-of-season soil samples, Mehlich-3 P and the phosphate saturation index (PSI: Mehlich-3 Al/P*100) increased with the application rate of P. Both soil P and PSI were higher in unfumigated control plots than plots fumigated with Vapam and in subplots planted in Ivory Russet than Russet Burbank. It is unclear why the two cultivars showed similar yield responses to P treatment when Ivory Russet has shown the stronger response of the two in the past. The robust yield response of Russet Burbank was not due to a lack of available P in the soil. Neither cultivar reached a point at which additional P fertilizer had diminishing returns in tuber size, yield, or tuber specific gravity. Adding mycorrhizal fungi had no significant effect on total yield, indicating that P acquisition in potato plants was not limited by access to mycorrhizal associates. At equivalent P rates, banded application showed benefits to yield, suggesting that root spread may limit P use efficiency in potatoes. Elevated end-of-season Mehlich-3 P and PSI under high application rates of P suggest that the increase in yield with higher P rate comes at a potential cost in increased P losses to the environment.

Background

Potato yield often responds positively to phosphorus (P) applications, even where soil-test P concentrations are high. Consistent with this observation, University of Minnesota Extension recommends a P fertilization rate of 75 lbs·ac^{-1} P_2O_5 in soils with Bray P concentrations over 50 ppm when a yield of at least 400 cwt·ac^{-1} is desired. Yield responses have been observed at much higher application rates, as well – as high as 150 lbs·ac^{-1} P_2O_5 in acidic, irrigated soils.

The fact that potatoes respond positively to P applications even in soils with high soil-test P concentrations suggests that potato plants are not efficient at taking up soil P. This inefficiency has at least two possible causes. First, potato plant root systems rarely extend much more than two feet into the soil, limiting the amount of soil P they have access to. Second, low availability of mycorrhizal associates or poor ability to form mycorrhizal associations may limit the roots' effectiveness at exploiting the P resources within their reach.

The extensiveness of the plant's root system and its ability to form mycorrhizal associations may be influenced by its genetics, so that different cultivars may show different yield responses to P rate. Our previous research at the Sand Plain Research Farm in Becker, MN, has shown that the cultivars Russet Burbank and Ivory Russet differ in their P responses. In a 2019 P response study, in soils with Bray P concentrations of 64 to 78 ppm, the yield of Ivory Russet plants increased with P rate at application rates from 125 to 250 lbs·ac^{-1} P_2O_5. Meanwhile, in soils with much lower Bray P (28 to 31 ppm), Russet Burbank yield did not respond to P rate at application rates between 0 and 80 lbs·ac^{-1} P_2O_5, a situation where a stronger yield response would be expected. This difference in P response was confirmed in a 2020 study in which Ivory Russet yield increased significantly with P rate at two sites with different soil-test P (126 vs. 95 ppm Bray; 198 vs. 136 ppm Mehlich-3 P), in which Ivory Russet showed a significant positive yield response to P in both sites while Russet Burbank did not, although treatments in Russet Burbank receiving P had significantly higher yield than the zero-P check treatment. As a determinate cultivar, Ivory Russet may have a less extensive root system than indeterminate Russet Burbank. There may also be differences between the two cultivars in terms of their potential to form mycorrhizal associations.

If P use efficiency is limited by the ability of plants to capture P within the range of their root systems, and if mycorrhizal associations enhance this ability, then soil fumigation to control soil-borne pathogens (including fungal pathogens), may be detrimental to P use efficiency. If so, applying mycorrhizal products at planting might fully or partially reverse this effect, increasing P use efficiency in fumigated soils more than unfumigated soils, where native mycorrhizal fungi may be more abundant.

Another factor affecting P uptake is placement. If potato P uptake is limited by the extensiveness of the plant's root network, P uptake efficiency could be improved by placing P closer to the plants through banded application.

Bray P may not be the best indicator of the potential for potatoes to respond to P application in acid soils. Research in Eastern Canada has found that a simple P saturation index (PSI; Mehlich-3 P / Mehlich-3 Al * 100) may work better for this purpose, since it accounts for fixation of available P by soluble Al, which is more abundant at lower soil pH. The researchers suggest two critical 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 to minimize P losses to leaching.

The objectives of this study were to evaluate how potato yield responses to P rate are affected by (1) cultivar, (2) soil fumigation with Vapam, (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 2020 on a Hubbard loamy sand soil. The previous crop was soybeans. A split-split-plot randomized complete block design was used. Whole plots were defined by fumigation treatment, each plot either receiving Vapam in the fall before planting or no fumigant. Each plot was divided into two subplots defined by cultivar – either Ivory Russet or Russet Burbank. Each subplot was further divided into nine sub-subplots, each receiving one of nine P application treatments: (1) a check treatment receiving no P; four treatments receiving (2) 75, (3) 130, (4) 300, or (5) 450 lbs·ac^{-1} P_2O_5 as triple super phosphate (TSP; 0-45-0-15Ca) broadcast before planting; two treatments being inoculated in-furrow with the mycorrhizal product MycoGold Liquid at planting and receiving either (6) zero or (7) 150 lbs·ac^{-1} P_2O_5 as TSP broadcast before planting; and two treatments receiving either (8) 75 or (9) 150 lbs·ac^{-1} P_2O_5 as TSP banded at planting. A summary of these treatments is presented in Table 1.

Initial soil characteristics

To measure initial soil characteristics, soil samples to depths of six inches and two feet were collected from both fumigation treatments in each block on April 1, 2021. The six-inch samples were analyzed for Bray P, NH_4-acetate-soluble K, hot-water-soluble B, Ca-phosphate extractable SO_4^{2-}-S, pH, loss-on-ignition organic matter content, and Mehlich-3 P, Al, Mg, Mn, Fe, Zn, and Cu. The two-foot samples were analyzed for NH_4^+-N and NO_3^--N concentrations using a Wescan Nitrogen Analyzer. The results of these analyses are presented in Table 2.

Treatment applications

Vapam was injected at inches at a rate of 50 gal·ac^{-1} to the appropriate plot in each block on October 14, 2020. The field was irrigated immediately after fumigant application. On April 14, 2021, 165 lbs·ac^{-1} K_2O and 22 lbs·ac^{-1} S were broadcast applied as 200 lbs·ac^{-1} MOP (0-0-60) and 200 lbs·ac^{-1} SulPoMag (0-0-22-21S-11Mg). TSP was broadcast in treatments 2-5 and 7 on April 19 (blocks 1 & 2) and 20 (blocks 3 & 4).

The subplots were planted with either Ivory Russet or Russet Burbank on April 28 (blocks 1 & 2) and 29 (blocks 3 & 4). TSP was mechanically banded to either side of each furrow at row opening in treatments 8 and 9. Two- to three-ounce cut seed potatoes were planted by hand in the open furrows, with 12 inches between tubers within the rows and 3-foot spacing between rows. Before row closure on April 29, MycoGold Liquid Inoculant was applied in-furrow with a backpack sprayer at a rate of 2 oz·ac^{-1} to tubers in treatments 6 and 7. At row closure, a blend of 87 lbs·ac^{-1} urea (46-0-0), 233 lbs·ac^{-1} MOP, 191 lbs·ac^{-1} SulPoMag, 2.8 lbs·ac^{-1} $ZnSO_4$ (35.5% Zn, 17.5% S), and 3.3 lbs·ac^{-1} Boron 15 (15% B) was mechanically banded in all treatments, supplying 40 lbs·ac^{-1} N, 180 lbs·ac^{-1} K_2O, 40 lbs·ac^{-1} S, 21 lbs·ac^{-1} Mg, 1 lb·ac^{-1} Zn, and 0.5 lbs·ac^{-1} B. All treatments received 150 lbs·ac^{-1} N as ESN (44-0-0, Nutrien, Ltd.) and 60 lbs·ac^{-1} N as urea mechanically banded at hilling so that 250 lbs·ac^{-1} N were applied in total.

Petiole sampling

Petioles were collected 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. They will be analyzed for nitrate concentration using a Wescan

Nitrogen Analyzer and for P concentration at the University of Minnesota Research Analytical Laboratory using an ICP spectrometer.

Harvest

Vines were chopped with a flail mower on September 8. Tubers were harvested from the central 18 feet from middle two rows in each sub-subplot in blocks 1-3 on September 22 and block 4 the following day. Most tubers were machine-sorted on September 28-29 and October 1. Due to an equipment failure, the remaining tubers were sorted by hand on October 8. A 25-tuber subsample was collected for each plot and analyzed 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 September 30 and analyzed for pH and Mehlich-3 Al and P.

Statistical analyses

Dependent variables were analyzed as functions of fumigation treatment, cultivar, P treatment, their interactions, and block using the GLIMMIX procedure in SAS 9.4. The effects of whole plot (fumigation*block) and subplots (fumigation*cultivar*block) were treated as fixed effects. If the effects of fumigation, cultivar, P treatment, or their interactions were statistically significant at $P \leq 0.10$), pairwise comparisons were evaluated using Fisher's LSD with the DIFF option in the LSMEANS statement of the model. Pairs of values were considered different if the difference was at least marginally significant ($P \leq 0.10$). Five treatment comparisons 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

Tuber yield

Results for tuber yield are presented in Table 3. Averaged between cultivars and across P treatments, the plots fumigated with Vapam had higher total, marketable, and U.S. No. 1 yields, but lower U.S. No. 2 yields, than the non-fumigated control plots. Averaged across fumigation treatments and P treatments, Russet Burbank had higher total, marketable, and U.S. No. 1 yields than Ivory Russet. The effect of fumigation on yield was larger in Russet Burbank than Ivory Russet, resulting in a significant effect of the fumigant*cultivar interaction (Figure 1). Total, marketable, and U.S. No.1 yield were also related to P treatment. Yield linearly increased with application rate of P for both cultivars. Additionally, total and marketable yield were higher in the treatments receiving P in a banded application (treatments 8 and 9) than in the corresponding treatments receiving a broadcast application (treatments 2 and 3). The effect of the interaction between fumigation treatment and P treatment on marketable yield was significant, with the linear regression line of the yield response to P rate being steeper in Vapam-treated plots than unfumigated control plots (Figure 2). Based on the equations of these regression lines, the treatments receiving 75 and 150 $lbs \cdot ac^{-1}$ P_2O_5 in banded applications (P treatments 8 and 9, respectively) produced yields equivalent to what would be obtained by broadcasting 76 and 241 $lbs \cdot ac^{-1}$ P_2O_5, respectively, in non-fumigated control plots and 194 and 301 $lbs \cdot ac^{-1}$ P_2O_5, respectively, in Vapam-treated plots. U.S. No. 2 yield was also related to P treatment, with the treatments receiving mycorrhizae (P treatments 6 and 7) having lower U.S. No.2 yields than the corresponding treatments without mycorrhizae (P treatments 1 and 3).

Averaged across P treatments, subplots planted in Ivory Russet and fumigated with Vapam had a larger percentage of their yield in tubers over six ounces than unfumigated control plots with Ivory Russet or Russet Burbank subplots in fumigated or unfumigated plots, all of which had similar percentages of yield in tubers over six ounces to each other. The percentage of yield in tubers over six ounces was not related to P treatment. The effect of the interaction between fumigation treatment and P treatment on the percentage of yield represented by tubers over ten ounces was marginally significant ($P < 0.10$), but there was no clear pattern to which treatments had more yield in tubers over ten ounces with Vapam application (treatments 3, 5, and 9) and which had less (treatment 2).

Tuber quality

Results for tuber quality are presented in Table 4. Hollow heart and brown center in Russet Burbank were less common in Vapam-fumigated plots than unfumigated control plots. The prevalence of either defect in Russet Burbank was more consistent across P treatments in Vapam-treated plots than unfumigated plots, in which some P treatments had hollow heart in up to 15% of tubers. In unfumigated control plots, the prevalence of hollow heart or brown center and the effect of fumigation on prevalence were unrelated to P rate or the use of the mycorrhizal product, but brown center was somewhat more prevalent in sub-subplots that received a banded application of P (treatments 8 and 9) than those where P was broadcast-applied at the same rates (treatments 2 and 3). In contrast, since both defects were rare or absent in Ivory Russet, their prevalence responded to neither fumigation treatment nor P treatment in this cultivar, resulting in significant three-way interaction of cultivar, fumigation treatment, and P treatment.

A three-way interaction effect was also observed in the prevalence of common scab. Russet Burbank had a lower average prevalence of scab than Ivory Russet, and its scab prevalence was therefore less responsive to fumigation treatment and P treatment. Among subplots with Ivory Russet, the prevalence of scab and the effect of fumigation on scab prevalence varied among P treatments, but neither scab prevalence nor the effect of fumigation on scab were related to P rate or banded application of P. However, scab was more prevalent, overall, in the treatments receiving MycoGold Liquid (treatments 6 and 7) than in the matched control treatments (treatments 1 and 3).

Tuber specific gravity and dry matter content were higher in Vapam-fumigated plots than unfumigated control plots and in Ivory Russet tubers than Russet Burbank tubers. Specific gravity and dry matter content increased with increasing P rate but were not significantly affected by the method of P application (banded vs. broadcast) or the addition of mycorrhizal fungi. Specific gravity exhibited a more pronounced response to P rate in plots fumigated with Vapam than unfumigated control plots (Figure 3), resulting in a marginally significant ($P < 0.10$) effect of the interaction between fumigation and P treatment.

End-of-season soil P, PSI, and pH

Results for end-of-season soil Mehlich-3 Al and P concentration, PSI, and pH are presented in Table 5. Mehlich-3 Al concentration was higher in Vapam-fumigated plots than unfumigated control plots. Subplots with Ivory Russet potatoes had higher end-of season soil Al and P concentrations than those with Russet Burbank potatoes, on average. Mehlich-3P concentration was also related to P treatment, increasing linearly with P rate. The use of MycoGold and the method of P application had no significant effect on residual Al and P concentrations.

End-of-season PSI showed very similar responses to treatment as Mehlich-3 P, overall. PSI was higher in unfumigated control plots than Vapam-fumigated plots, and it was higher in subplots planted in Ivory Russet than those in Russet Burbank. PSI increased with P rate and was not significantly influenced by the use of MycoGold or banded P application. The effect of the interaction between cultivar and P treatment was significant. While PSI was higher when Ivory Russet was the cultivar regardless of P treatment (averaged across fumigation treatments), the difference between the two cultivars varied from treatment to treatment. The magnitude of this difference did not appear to be related to P rate, MycoGold, or banded application.

Soil pH was higher in unfumigated control plots than in Vapam-fumigated plots and in subplots with Russet Burbank than those with Ivory Russet. Among the broadcast treatments without MycoGold, pH decreased linearly with increasing P rate. MycoGold and banded application had no significant effect on end-of-season soil pH. The effect of the three-way interaction of fumigation, cultivar, and P treatment on soil pH was significant. The effect of P rate on pH appeared to be stronger in Russet Burbank than Ivory Russet and, among Russet Burbank subplots, it appeared to be stronger in plots fumigated with Vapam than unfumigated control plots. The apparent effects of MycoGold and banded application on soil pH varied with P rate, cultivar, and fumigation treatment.

Conclusions

Contrary to our expectations and prior experience, the two cultivars did not show significantly different yield responses to P rate in this study. It is not clear why the two cultivars responded to P rate similarly when Ivory Russet has shown a stronger response than Russet Burbank in the past, including in two fields in which a similar study was conducted in 2020. The soils in the current study had Bray and Mehlich-3 P concentrations intermediate between those of the two fields used in 2020 (Bray P: 105-115 ppm vs. 95 and 126 ppm; Mehlich-3 P: 162-172 ppm vs. 136 and 198 ppm), but a lower PSI than either of them (18.8-18.9% vs. 21.4% and 23.3%). Perhaps this lower PSI explains why Russet Burbank showed a significant yield response to P rate in 2021 and not 2020. However, given the neutral pH of the site (pH: 6.8 – 6.9) and a previously identified critical threshold PSI of 14.2% in mineral soils with pH over 5.5, this explanation seems unlikely.

Although we applied up to six times the recommended amount of P fertilizer, both cultivars showed linear yield and specific gravity responses to P rate across the range we tested. Since the percentage of yield represented by tubers over either six or ten ounces did not change significantly with P rate based on linear contrasts, the yield response to P rate was probably due less to tuber bulking than tuber set. Previous research has found that high rates of P fertilizer in soils with lower soil-test P concentrations promote tuber set, sometimes at the expense of tuber bulking. In these higher P testing soils, it is not clear why tuber bulking was apparently unaffected by P rate in this study.

Applying a MycoGold Liquid in-furrow decreased the yield of U.S. No. 2 tubers. It also increased the prevalence of common scab when P was applied at 150 $lbs \cdot ac^{-1}$ P_2O_5. However, it had no significant effect on other key yield and quality variables. These results indicate that access to mycorrhizal associates was not a major limitation on P use efficiency in potato, even after fumigation with Vapam.

In contrast to last year's results, banded application of P produced slightly but significantly higher total and marketable yield than broadcast application at the same rates in both cultivars. The effect of banded application on yield suggests that the extensiveness of the plant root system under some conditions may limit the ability of potato plants to take up available soil P.

The positive relationship between P rate and end-of-season Mehlich-3 P concentration and PSI suggests that, while increasing P rate increased tuber yield and, presumably, P uptake, potato plants did not make efficient use of the higher available P. Although high P rates may increase yield significantly, even in soils with high soil-test P, this higher yield comes at a cost in terms of the amount of available P left in the soil at the end of the year, potentially increasing P losses to the environment.

Table 1. Phosphorus fertilization treatments applied to Vapam-fumigated and unfumigated Ivory Russet and Russet Burbank potatoes.

Treatment			
Number	P_2O_5 rate (lbs/ac)	Application	Mycorrhizae?[1]
1	0	NA	No
2	75	Broadcast	No
3	130	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

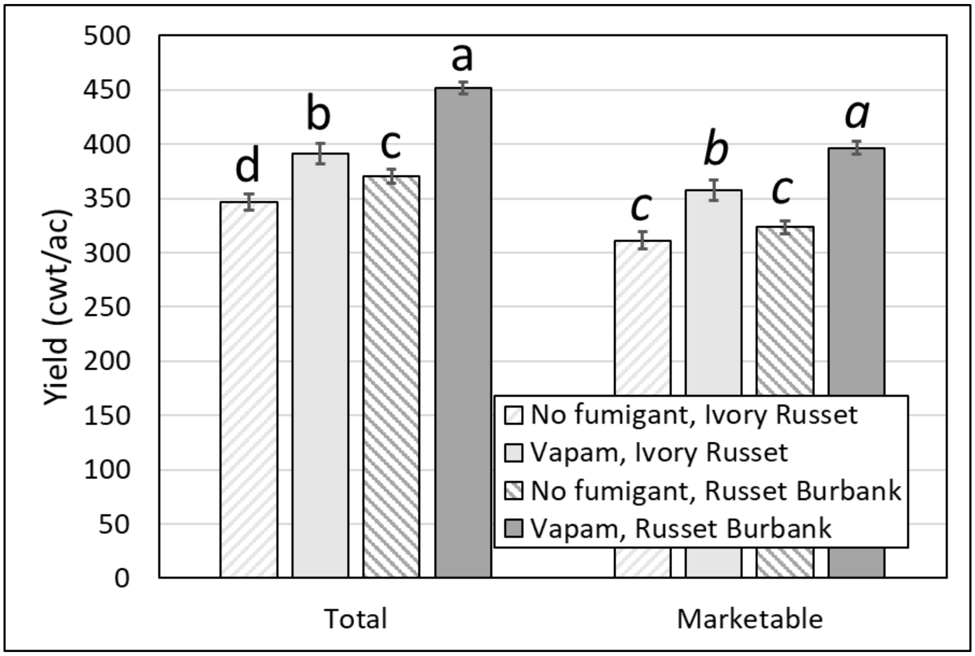
[1]Applied in-furrow at planting with a hand sprayer

Table 2. Soil characteristics before fertilizer application in Vapam-fumigated and unfumigated control plots.

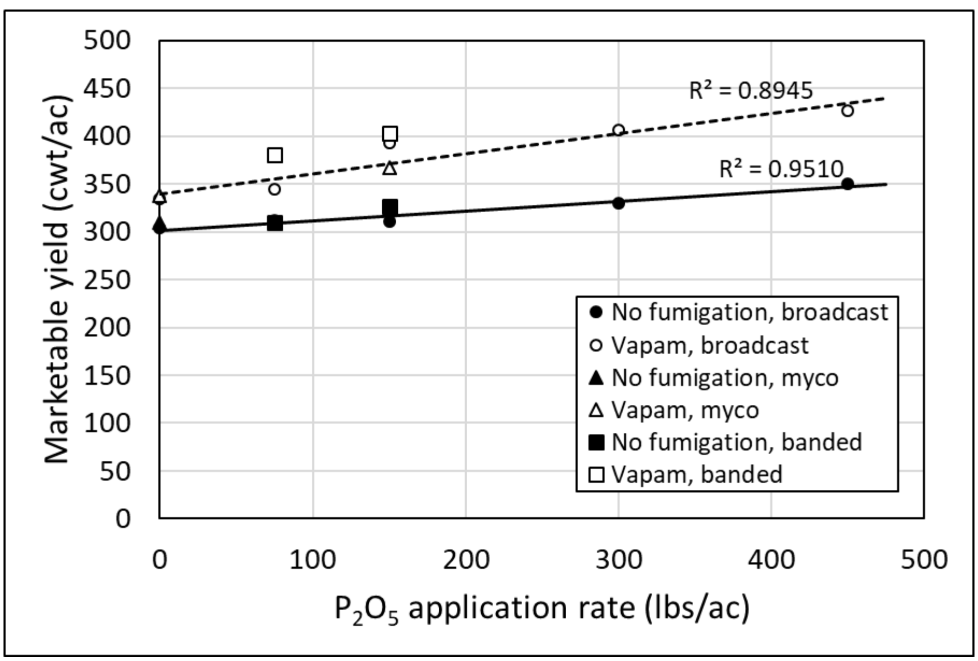
	0 - 6 inches															0 - 2 feet
Fumigation treatment	Bray P (ppm)	Mehlich-3 P (ppm)	Mehlich-3 Al (ppm)	PSI (%)	pH	Organic matter (%)	NH_4OAc-K	Mehlich-3 Ca	Mehlich-3 Mg	Mehlich-3 Mn	Mehlich-3 Fe	Mehlich-3 Zn	Mehlich-3 Cu	Hot water B	SO_4^{2-}-S	NO_3^--N (ppm)
							---------- ppm ----------									
Control	105	172	913	18.9	6.9	2.4	254	1256	273	35	105	4.9	1.4	0.3	6	6
Vapam	115	162	862	18.8	6.8	2.5	232	1126	241	34	103	4.6	1.3	0.3	6	

Table 3. 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	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	Average of both	Average of all	4.7	41 b	85 b	118 b	75 b	39 b	358 b	288 b	29 a	317 b	64 b	31
Vapam			4.0	45 a	95 a	141 a	86 a	56 a	422 a	352 a	25 b	377 a	67 a	34
Average of both	Ivory Russet	Average of all	3.5 b	35 b	87 b	128	77 b	43 b	369 b	306 b	29	335 b	67 a	32
	Russet Burbank		5.2 a	51 a	94 a	131	83 a	52 a	411 a	334 a	26	360 a	65 b	33
Average of both	Average of both	1: 0 lbs/ac, myc -	6.1	41	82	114 d	78 bcd	45	360 e	288 d	31	319 f	66	34
		2: 75 lbs/ac broad myc -	3.8	42	91	123 bcd	72 cd	42	370 e	304 cd	24	328 ef	64	31
		3: 150 lbs/ac broad myc -	4.7	40	87	135 ab	86 ab	43	391 cd	322 bc	29	351 bcd	68	33
		4: 300 lbs/ac broad myc -	2.5	48	96	140 a	81 abc	51	416 ab	341 ab	28	368 b	65	32
		5: 450 lbs/ac broad myc -	3.1	41	102	142 a	91 a	54	429 a	359 a	30	388 a	67	34
		6: 0 lbs/ac, myc +	5.5	45	86	116 cd	69 d	40	357 e	291 d	21	312 f	63	31
		7: 150 lbs/ac broad myc +	3.9	41	86	128 abc	79 bcd	55	389 d	323 bc	26	348 cd	67	34
		8: 75 lbs/ac band myc -	6.2	44	91	129 ab	81 abcd	44	389 d	320 bc	25	345 de	65	32
		9: 150 lbs/ac band myc -	3.1	44	91	138 a	83 ab	53	409 bc	334 b	30	365 bc	67	33
ANOVA effects		Fumigant	0.4370	*0.0891*	**0.0058**	**<0.0001**	**0.0008**	**<0.0001**	**<0.0001**	**<0.0001**	*0.0849*	**<0.0001**	**0.0257**	0.1099
		Cultivar	**0.0455**	**<0.0001**	**0.0341**	0.4726	*0.0667*	**0.0047**	**<0.0001**	**<0.0001**	0.1466	**<0.0001**	*0.0754*	0.4543
		P treatment	0.2480	0.7738	0.2896	**0.0016**	*0.0572*	0.2075	**<0.0001**	**<0.0001**	0.5031	**<0.0001**	0.5836	0.8683
		Fumigant*cultivar	0.8741	**0.0163**	**0.0167**	*0.0517*	0.9206	0.3471	**0.0009**	**0.0018**	**0.0092**	**0.0166**	**0.0483**	**0.0332**
		Fumigant*P treatment	0.7392	**0.0322**	0.8571	0.6276	**0.0112**	0.1321	0.2653	0.1196	0.5161	*0.0882*	0.5469	*0.0623*
		Cultivar*P treatment	0.1467	0.2954	0.6023	0.9690	0.2452	0.3062	0.8178	0.9968	0.1873	0.7994	0.2831	0.3891
		Fumigant*cultivar*P treatment	*0.0985*	0.8290	0.9798	0.8334	0.5139	0.7830	0.8581	0.9848	0.2806	0.9296	0.9604	0.8880
Contrasts on P treatment		P addition (1 v 2 - 5)	*0.0577*	0.6290	*0.0506*	**0.0008**	0.4414	0.6072	**<0.0001**	**<0.0001**	0.3600	**<0.0001**	0.9762	0.4012
		Linear P rate (1 - 5)	*0.0694*	0.5391	**0.0091**	**0.0002**	**0.0233**	*0.0560*	**<0.0001**	**<0.0001**	0.8809	**<0.0001**	0.5255	0.8576
		Quadratic P rate (1 - 5)	0.3473	0.3596	0.9569	*0.0805*	0.6875	0.6150	0.2871	0.3709	0.4847	0.4845	0.9852	0.3639
		Mycorrhizae (1&3 v 6&7)	0.5639	0.4549	0.7957	0.7003	*0.0871*	0.4057	0.7398	0.8543	*0.0534*	0.5321	0.3810	0.6146
		Broadcast v band (2&3 v 8&9)	0.7246	0.3056	0.7531	0.4419	0.5605	0.2009	**0.0247**	0.1263	0.7298	*0.0655*	0.8167	0.7221



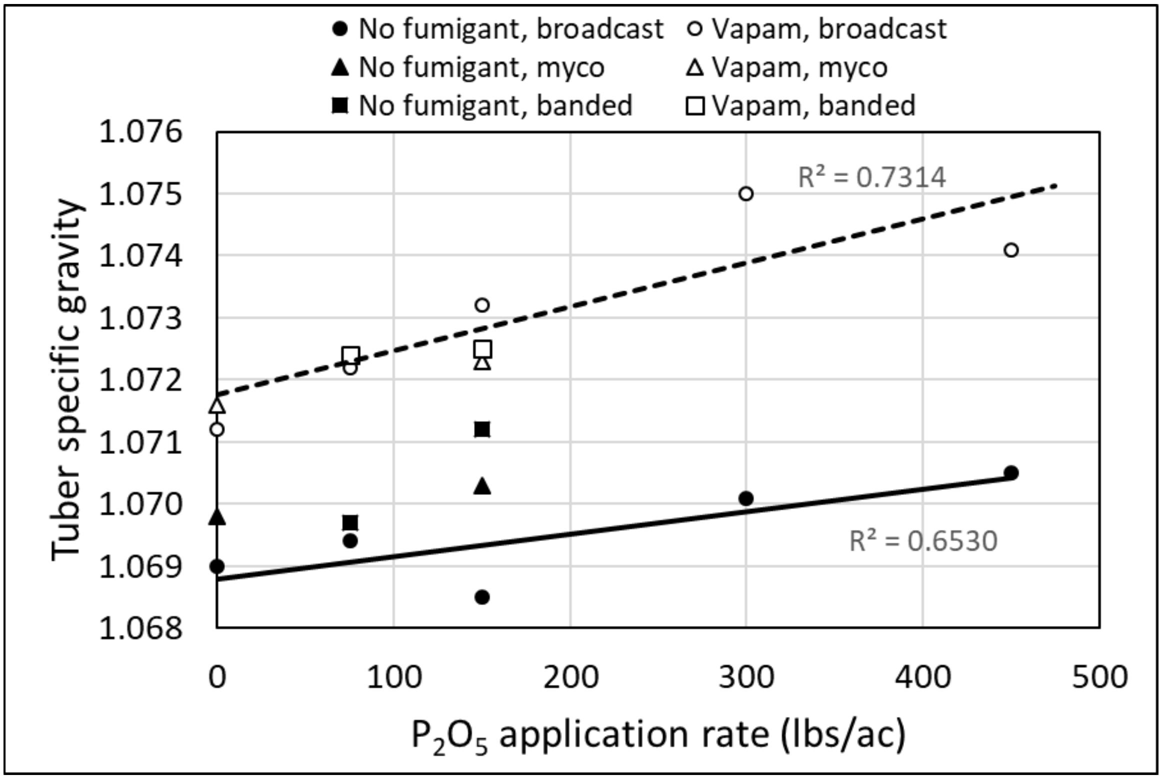
Yield (cwt/ac)
0
50
100
150
200
250
300
350
400
450
500
d
b
c
a
c
b
c
a
Total
Marketable
No fumigant, Ivory Russet
Vapam, Ivory Russet
No fumigant, Russet Burbank
Vapam, Russet Burbank



Marketable yield (cwt/ac)
0
50
100
150
200
250
300
350
400
450
500
R² = 0.8945
R² = 0.9510
No fumigation, broadcast
Vapam, broadcast
No fumigation, myco
Vapam, myco
No fumigation, banded
Vapam, banded
0
100
200
300
400
500
P2O5 application rate (lbs/ac)

Table 4. Effects of fumigation treatment, cultivar, and P treatment on tuber quality. 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			Hollow heart	Brown center	Scab	Specific gravity	Dry matter (%)
Fumigant	Cultivar	P treatment	Percent of tubers				
None	Average of both	Average of all	4.3 a	3.2 a	6.7 a	1.0698 b	18.6 b
Vapam			1.6 b	0.9 b	2.9 b	1.0727 a	19.2 a
Average of both	Ivory Russet	Average of all	0.1 b	0.0 b	7.4 a	1.0756 a	19.9 a
	Russet Burbank		5.8 a	4.1 a	2.2 b	1.0669 b	17.9 b
Average of both	Average of both	1: 0 lbs/ac, myc -	2.8	1.0 c	3.3 c	1.0701 e	18.3 e
		2: 75 lbs/ac broad myc -	2.8	1.3 bc	4.8 bc	1.0708 cde	18.7 cde
		3: 150 lbs/ac broad myc -	1.5	1.3 bc	3.5 c	1.0708 cde	19.1 abcd
		4: 300 lbs/ac broad myc -	3.5	3.0 ab	3.3 c	1.0726 a	19.3 ab
		5: 450 lbs/ac broad myc -	3.3	1.8 bc	5.5 abc	1.0723 ab	19.5 a
		6: 0 lbs/ac, myc +	3.0	2.0 bc	3.8 c	1.0707 de	18.5 e
		7: 150 lbs/ac broad myc +	3.3	2.8 abc	7.8 a	1.0713 bcd	18.6 de
		8: 75 lbs/ac band myc -	2.0	1.0 d	7.5 ab	1.0710 cde	18.8 bcde
		9: 150 lbs/ac band myc -	4.5	4.5 a	4.0 c	1.0719 abc	19.3 abc
ANOVA effects		Fumigant	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**0.0019**
		Cultivar	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
		P treatment	0.4510	**0.0289**	**0.0487**	**0.0057**	**0.0078**
		Fumigant*cultivar	**<0.0001**	**<0.0001**	*0.0928*	0.8054	0.7199
		Fumigant*P treatment	*0.0815*	**0.0280**	**0.0048**	*0.0819*	0.1761
		Cultivar*P treatment	0.3073	**0.0289**	*0.0596*	0.8109	0.8830
		Fumigant*cultivar*P treatment	*0.0799*	**0.0280**	**0.0003**	0.3758	0.9747
Contrasts on P treatment		P addition (1 v 2 - 5)	0.9936	0.3487	0.4725	**0.0069**	**0.0023**
		Linear P rate (1 - 5)	0.4117	0.2057	0.3929	**<0.0001**	**0.0005**
		Quadratic P rate (1 - 5)	0.5940	0.3436	0.4803	0.2721	0.1762
		Mycorrhizae (1&3 v 6&7)	0.2526	0.1108	*0.0559*	0.2712	0.4725
		Broadcast v band (2&3 v 8&9)	0.2047	*0.0581*	0.1886	0.1784	0.7480



No fumigant, broadcast
Vapam, broadcast
No fumigant, myco
Vapam, myco
No fumigant, banded
Vapam, banded
R² = 0.7314
R² = 0.6530
Tuber specific gravity
1.076
1.075
1.074
1.073
1.072
1.071
1.070
1.069
1.068
0
100
200
300
400
500
P2O5 application rate (lbs/ac)

Table 5. Effects of fumigation treatment, cultivar, and P treatment on end-of-season soil Mehlich-3 Al and P, phosphate saturation index (PSI), and pH. 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			Mehlich-3 concentration (ppm)		PSI (%)	pH
Fumigant	Cultivar	P treatment	Al	P		
None	Average of both	Average of all	992 b	221	22.2 a	6.63 a
Vapam	Average of both	Average of all	1024 a	219	21.4 b	6.57 b
Average of both	Ivory Russet	Average of all	1026 a	236 a	23.0 a	6.58 b
Average of both	Russet Burbank	Average of all	990 b	204 b	20.6 b	6.62 a
Average of both	Average of both	1: 0 lbs/ac, myc -	1001	192 e	19.2 f	6.69 a
		2: 75 lbs/ac broad myc -	992	202 de	20.4 e	6.62 abc
		3: 150 lbs/ac broad myc -	1019	221 c	21.7 cd	6.62 abc
		4: 300 lbs/ac broad myc -	993	241 b	24.2 b	6.60 bc
		5: 450 lbs/ac broad myc -	1004	273 a	27.2 a	6.49 d
		6: 0 lbs/ac, myc +	1018	198 e	19.3 f	6.62 abc
		7: 150 lbs/ac broad myc +	1003	217 c	21.6 cd	6.64 ab
		8: 75 lbs/ac band myc -	1027	213 cd	20.8 de	6.56 cd
		9: 150 lbs/ac band myc -	1013	221 c	21.8 c	6.58 bc
ANOVA effects		Fumigant	**0.0105**	0.6942	**0.0027**	**0.0058**
		Cultivar	**0.0033**	**<0.0001**	**<0.0001**	***0.0629***
		Fumigant*cultivar	0.1260	0.1983	0.8452	0.1795
		P treatment	0.8952	**<0.0001**	**<0.0001**	**0.0118**
		Fumigant*P treatment	0.5122	0.6253	0.2819	0.3723
		Cultivar*P treatment	0.9259	0.4364	**0.0479**	0.5559
		Fumigant*cultivar*P treatment	0.1297	0.1278	0.5569	**0.0360**
Contrasts on P treatment		P addition (1 v 2 - 5)	0.9560	**<0.0001**	**<0.0001**	**0.0055**
		Linear P rate (1 - 5)	0.9893	**<0.0001**	**<0.0001**	**0.0002**
		Quadratic P rate (1 - 5)	0.8786	0.7849	0.5297	0.6762
		Mycorrhizae (1&3 v 6&7)	0.9799	0.8645	0.8957	0.4553
		Broadcast v band (2&3 v 8&9)	0.4352	0.3617	0.5666	0.1489