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

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Summary

Potato yield responses to phosphorus (P) fertilizer are often positive even in soils with high Bray P concentrations, in excess of 50 ppm. Previous research at the Sand Plain Research Farm (SPRF) in Becker, MN, has indicated that the cultivar Ivory Russet may have a stronger yield response to P rate than Russet Burbank. Potato yield responses to P rate in high-P soils indicate that P uptake in potatoes is limited by something other than soil-test P concentration. Possibilities include the relative shallowness of potato root systems and a lack of mycorrhizal associates, especially in fumigated soils. Alternatively, Bray P concentration may not adequately measure the true availability of P in acid soils. The ratio of Mehlich-3 P concentration to Melich-3 aluminum (Al) concentration, called the P saturation index (PSI), may be a better indicator predictor of yield responses to P rate. The objectives of this study were to evaluate how potato yield responses to P rate are affected by (1) cultivar, (2) soil fumigation with metam sodium, (3) applying a mycorrhizal product at planting, and (4) banded versus broadcast application of P fertilizer, and (5) to evaluate PSI, Bray P, and Mehlich-3 P as predictors of potato yield response to P. The study was conducted in two sites, one at SPRF, in which the soil was not fumigated, and one at a nearby grower's field , in which the soil was fumigated with metam sodium in the previous fall. In each field, a split-plot randomized complete block design was used, with cultivar (Ivory Russet or Russet Burbank) as the whole-plot effect and P treatment as the subplot effect. Nine P treatments were tested: (1) a check treatment receiving no P fertilizer; treatments receiving triple super phosphate (TSP) at rates of (2) 75 lbs·ac^{-1} P_2O_5, (3) 150 lbs·ac^{-1} P_2O_5, (4) 300 lbs·ac^{-1} P_2O_5, and (5) 450 lbs·ac^{-1} P_2O_5 broadcast before planting; two treatments to which mycorrhizal fungal inoculum was applied in-furrow at planting after (6) no P or (7) 150 lbs·ac^{-1} P_2O_5 were broadcast before planting; and treatments receiving (8) 75 lbs·ac^{-1} P_2O_5 and (9) 150 lbs·ac^{-1} P_2O_5 as TSP banded at row opening. Ivory Russet showed a positive yield response to P rate in both sites, while Russet Burbank did not. Banded application of P had no effect on yield at SPRF and a negative effect on total and marketable Ivory Russet yield and U.S. No. 2 Russet Burbank yield at the grower field. Tuber yield response to P rate was similar between the two sites for each cultivar, indicating that fumigation did not alter P uptake. Inoculation with mycorrhizal fungi at planting had few effects on yield, and the only positive effects were observed in Russet Burbank in the non-fumigated soils of SPRF. The prevalence of hollow heart and brown center increased significantly or marginally significantly with P rate in both cultivars at SPRF and Ivory Russet at the grower field. The prevalence of scab was much higher in the non-fumigated SPRF site than the fumigated grower site. Overall, the results of this study suggest that the P use efficiency of Ivory Russet is poor compared to Russet Burbank, but the issue is not remedied by banded P application, inoculation with mycorrhizal fungi, or foregoing soil fumigation. The differences in Bray P, Mehlich-3 P, and PSI between the two sites used in this study were not large enough to substantially alter the P responses of either cultivar.

Introduction

Potato yield responses to phosphorus (P) fertilizer rare often positive even in soils with high soil-test P concentrations. For example, in soils with Bray P concentrations over 50 ppm, when yields of 400 cwt·ac^{-1} or higher are desired, the University of Minnesota Extension recommended rate of P fertilization is 75 lbs·ac^{-1} P_2O_5, and it is noted that responses in acidic, irrigated soils have been observed at application rates as high as 150 lbs·ac^{-1} P_2O_5.

Positive potato yield responses to differences in P rate even in high-P soils and at high application rates suggest that potato plants are not efficient at taking up soil P. Potatoes have relatively shallow root systems, rarely extending much below two feet into the soil, limiting the volume of soil from which they are able to acquire P. In addition, potatoes tend not to form extensive mycorrhizal associations, especially following fumigation, limiting how thoroughly they exploit P resources in the soil within the range of their root systems.

Both root system extent and success in forming mycorrhizal associations may be greatly affected by potato plant genetics. Different cultivars may therefore show different yield responses to P rate. In a P response study conducted at the Sand Plain Research Farm in Becker, MN, in 2019, the Ivory Russet showed a positive yield response at application rates between 125 and 250 $lbs \cdot ac^{-1}$ P_2O_5 in soil where Bray P concentration ranged from 64 to 78 ppm. In a separate study in the same facility in the same year, Russet Burbank showed no yield response to P rate at rates of 0 or 80 $lbs \cdot ac^{-1}$ P_2O_5 in soil with 28 to 31 ppm Bray P. As a determinate cultivar, Ivory Russet may have a less extensive root system than indeterminate Russet Burbank, and there may also be differences between the two cultivars in terms of their efficiency at forming mycorrhizal associations.

If mycorrhizal associations affect P use efficiency, it is plausible that soil fumigation, which is frequently used to control soil-borne pathogens, including fungal pathogens such as *Verticillium*, has a negative effect on potato P use efficiency. If so, this negative effect may be partially or fully compensated for by applying mycorrhizal products to potato fields at planting. Alternatively, if potato P uptake is limited more by the extensiveness of potato root systems than by their effectiveness at absorbing P within range of their root and mycorrhizal networks, P uptake efficiency might be improved by placing P closer to the plants through banded application.

Finally, it is possible that Bray P alone is not the best indicator of potato P response in acid soils. Research in Eastern Canada has found that the P saturation index (PSI), the ratio of Melich-3 extractable P to Melich-3 extractable aluminum (Al), may be a better predictor.

The objectives of this study were to evaluate how potato yield responses to P rate are affected by (1) cultivar, (2) soil fumigation with metam sodium, (3) applying a mycorrhizal product at planting, and (4) banded versus broadcast application of P fertilizer, and (5) to evaluate PSI, Bray P, and Mehlich-3 P as predictors of potato yield response to P.

Methods

Study design

The study was conducted at two sites in 2020, one in a non-fumigated field on the Sand Plain Research Farm (SPRF) in Becker, MN, and one in a metam-sodium-fumigated grower field approximately one mile to the east, on Hubbard loamy sand soils. Nine treatments were applied to 20-by-12-foot subplots in a split-plot randomized complete block design in each site, with whole plots defined by the potato cultivar planted: Russet Burbank or Ivory Russet. The treatments included (1) a check treatment receiving no P fertilizer; treatments receiving triple super phosphate (TSP) at rates of (2) 75 $lbs \cdot ac^{-1}$ P_2O_5, (3) 150 $lbs \cdot ac^{-1}$ P_2O_5, (4) 300 $lbs \cdot ac^{-1}$ P_2O_5, and (5) 450 $lbs \cdot ac^{-1}$ P_2O_5 broadcast before planting; (6) a check treatment receiving no P, to which the mycorrhizal product MycoGold (MycoGold LLC) was applied in-furrow at planting with a hand sprayer; (7) a treatment receiving 150 $lbs \cdot ac^{-1}$ P_2O_5 broadcast before planting plus MycoGold in-furrow at planting; and treatments receiving (8) 75 $lbs \cdot ac^{-1}$ P_2O_5 and (9) 150 $lbs \cdot ac^{-1}$ P_2O_5 as TSP banded at row opening. A summary of these treatments is presented in Table 1.

Initial soil characteristics

To measure soil characteristics before fertilizer treatments were applied, soil samples to a depth of six inches were collected from each replicate in each study site on April 17. Samples were analyzed for Bray P, Mehlich-3-extractable P, Al, Mg, Mn, Fe, Zn, and Cu, acetate-extractable K and Ca, hot-water-extractable B, SO_4^{2-}-S, pH, and loss-on-ignition organic matter content. PSI was calculated as the ratio of Mehlich-3 P to Mehlich-3 Al times 100. In addition, two-foot soil samples were collected by replicate in each site and analyzed for NO_3^--N concentration using a Wescan Nitrogen Analyzer. Results of these analyses are presented in Table 2. Potassium fertilizer was applied to the grower site in fall 2019, as well as gypsum in the spring, before soil samples were taken, and K and S concentrations were therefore elevated at this site.

Planting and emergence

The SPRF site received 164 lbs·ac^{-1} K_2O and 22 lbs·ac^{-1} S as 200 lbs·ac^{-1} MOP (0-0-60) and 200 lbs·ac^{-1} SulPoMag (0-0-22-22S-11Mg) on April 18. TSP was broadcast applied by hand in treatments 2 – 5 and 7 at rates indicated by treatment on April 29 at the grower site and May 5 at the SPRF site. Rows were opened and TSP mechanically banded in treatments 8 and 9 at rates indicated by treatment on April 29 at the grower site and May 6 at the SPRF site. In addition, all plots in both fields received 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 as a combination of 87 lbs·ac^{-1} urea (46-0-0), 43 lbs·ac^{-1} MOP, 1191 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). On April 30 in the grower site and May 6 in the SPRF site, 2-3-oz. seed potatoes were planted by hand in each plot with one-foot spacing within rows and three-foot spacing between rows. Before row closure, tubers were treated with an in-furrow application of MycoGold Potato Blend, which includes mycorrhizal fungi, at a rate of 2 oz·ac^{-1}.

At the grower site, 220 lbs·ac^{-1} N were applied as ESN (44-0-0; Nutrien, Ltd.) at emergence (May 13) together with 90 lbs·ac^{-1} N as 28% urea and ammonium nitrate (UAN). At the SPRF site, 150 lbs·ac^{-1} N were applied as ESN with 60 lbs·ac^{-1} N as urea at emergence (May 20). Plant stand was measured in the central 18 feet of the central two rows of each subplot on June 4, 11, and 22 in each site, and the number of stems per plant was determined for ten plants from the same two rows on June 15 and 22.

Petiole sampling

Petioles were collected from the grower field on June 25 and July 6 and 27 and from the SPRF field on June 25 and July 6 and 23. The petiole of the fourth mature leaf from the shoot tip was collected for 20 leaves per plot. Petioles were dried at 140°F until their weight was stable and then ground. They will be analyzed for P concentration by the University of Minnesota Research Analytical Laboratory using inductively coupled plasmolysis.

Harvest

Vines were killed with desiccant on September 4 at the grower site, 127 days after planting, and chopped on September 15. Vines were killed by chopping on September 9 at the SPRF site, 126 days after planting. Tubers were harvested from the central 18 feet of the middle two rows of each subplot on September 17 at the grower site and September 21 at the SPRF site. Tubers from the grower site were sorted on October 22-23, and those from the SPRF site were sorted on October

26-27. End-of-season soil samples were collected on September 18 at the grower site and October 7 at the SPRF site.

Data analysis

Data were analyzed with SAS 9.4m3® software (copyright 2015, SAS Institute, Inc.) using the MIXED procedure. Data were analyzed for each combination of site and cultivar separately, as functions of treatment and block. Means for each treatment were calculated and post-hoc pairwise comparisons between treatments made using the LSMEANS statement with the DIFF option. Pairwise comparisons were only evaluated where the P-value of the relevant effect in the model was less than 0.10, and pairwise comparisons with P-values less than 0.10 were considered significant. Four CONTRAST statements were used to evaluate particular treatment effects of interest:

1. The linear contrast on P rate, including treatments 1 – 5,
2. The quadratic contrast on P rate, including treatments 1 – 5,
3. A comparison of banded versus broadcast application, comparing treatments 2 and 3 with treatments 8 and 9, and
4. A comparison of treatments with and without added mycorrhizae, comparing treatments 1 and 3 with treatments 6 and 7.

Results and discussion

Initial soil characteristics

The initial soil characteristics of the study sites, before fertilizer treatments were applied but after MOP and gypsum were applied to the grower site, are presented in Table 2. Bray and Mehlich-3 P concentrations, Mehlich-3 Al concentration, and PSI were all higher in the SPRF site than the grower site. However, the Bray P concentration was very high (≥ 51 ppm) in both sites, and the PSI was well above the environmentally critical percentage identified in published research (15%). With a target yield of 500 cwt·ac^{-1}, current University of Minnesota Extension recommendations would call for the application of 75 lbs·ac^{-1} P_2O_5 in fields with Bray P concentrations in excess of 50 ppm.

Tuber yield

Results for Ivory Russet tuber yield at the grower site are presented in Table 3. The overall effect of treatment was significant for total yield, yield of U.S. No. 2 tubers, and marketable yield. Each of these measures of yield, as well as yield in the two largest size classes (10-14 oz. and > 14 oz.), increased linearly with P rate. The yield of U.S. No. 2 tubers and the percentage of yield in tubers over 6 oz. both showed quadratic responses to P rate, each having a lower value at the highest rate (450 lbs·ac^{-1} P_2O_5) than at the second-highest rate (300 lbs·ac^{-1} P_2O_5). Total and marketable yield, the yield of U.S. No. 1 tubers, and the yield of 10- to 14-oz. tubers were lower in the treatments in which P was banded at planting (treatments 8 and 9) than in the treatments in which P was broadcast before planting at the same rates (treatments 2 and 3). The mycorrhizal product had no significant effect on yield in this cultivar and this site.

Results for Russet Burbank tuber yield at the grower site are presented in Table 4. The yield of U.S. No. 2 tubers was lower in the treatments in which P was banded at planting (treatments 8 and 9) than the treatments in which it was broadcast before planting at the same rates (treatments 2 and 3). U.S. No. 2 tuber yield also had a marginally significant negative linear

relationship with the application rate of P. There were no other significant effects of treatment on yield in this cultivar and this site.

Results for Ivory Russet tuber yield at the SPRF site are presented in Table 5. As was true of Ivory Russet at the grower site, total and marketable yield were positively related to the application rate of P. The same was true of U.S. No. 1 yield and the yield of 4- to 6-oz. tubers, although yield in these categories was lowest at intermediate P rates (75 to 150 lbs·ac^{-1} P_2O_5). As was true at the grower site, the yield of U.S. No. 2 tubers was highest at the second-highest P rate (300 lbs·ac^{-1} P_2O_5), and the percentage of yield represented by tubers over 6 or 10 oz. was lower at the lowest and highest P rates (0 and 450 lbs·ac^{-1} P_2O_5, respectively) than at other P rates. However, unlike at the grower site, U.S. No. 2 yield was not positively related to P rate overall. Yields in all size classes less than 14 oz. tended to increase as the application rate of P increased. Whether P fertilizer was broadcast before planting or banded at planting did not significantly affect tuber yield. The treatments receiving mycorrhizae (treatments 6 and7) had marginally significantly lower yields of tubers over 14 oz. than the treatments receiving P at the same rates with no added mycorrhizae (treatments 1 and 3).

Results for Russet Burbank tuber yield at the SPRF site are presented in Table 6. As was true at the grower site, Russet Burbank showed few significant responses to P treatment. The yield of 6- to 10-oz. tubers was significantly related to treatment, and the percentages of yield represented by tubers over 6 or 10 oz. were marginally significantly related to treatment with no consistent relationship to P rate. The contrast comparing treatments receiving mycorrhizae (treatments 6 and 7) with otherwise similar treatments receiving no mycorrhizae (treatments 1 and 3) was marginally significant for the yield of 6- to 10-oz. tubers and the percentage of yield represented by tubers over 6 oz. In each case, the values were higher in the treatments receiving mycorrhizae (treatments 6 and 7).

Overall, the application rate of P had a much stronger effect on yield in Ivory Russet than Russet Burbank. In both fields, total and marketable yields of Ivory Russet tubers increased as P rate increased, and the percentage of yield represented by tubers over 6 oz. peaked at an intermediate P rate (75 or 300 lbs·ac^{-1} P_2O_5). That Ivory Russet responded more strongly to P rate than Russet Burbank may reflect a less extensive root system in the former cultivar, which has determinate growth, than in the latter, which is indeterminate. It is also possible that Ivory Russet is less efficient than Russet Burbank at taking up soil P within the range of its root system, whether or not one cultivar has a more extensive root system than the other. The peak in tuber size at intermediate P rates may indicate that very high P rates result in increased tuber set in Ivory Russet.

Banded P fertilizer application had a negative effect on Ivory Russet total and marketable yield at the grower site, but not at SPRF. Banded application also decreased the yield of U.S. No. 2 tubers in Russet Burbank grown at the grower site. Banded application was expected to improve plant access to P, if the extensiveness of the root system limited P uptake. The fact that the few significant effects of banded application on yield in this study were negative indicates that this approach does not increase P uptake, although it is possible that tissue P concentrations will prove to be higher in the banded-application treatments. It is not clear why banded application only affected yield at the grower site. However, excessive P fertilizer application has been found to negatively impact crops through its impacts on both the soil microbial community and Zn availability. It is possible that the microbial community at the grower site was more sensitive to P rate, perhaps as a result of soil fumigation. Petiole analysis may provide information related to the P-Zn interaction, but results for this test were not available at the time of this report.

The application of MycoGold, a product containing mycorrhizal fungi, had no effect on Ivory Russet yield beyond a marginally significant decrease in the yield of tubers over 14 oz. at SPRF. In Russet Burbank, the addition of mycorrhizae marginally significantly decreased U.S. No. 2 yield at the grower site, but it marginally significantly increased the yield of 6- to 10-oz. tubers and the percentage of yield in tubers over 6 oz. at SPRF. It was anticipated that inoculation with mycorrhizae would improve P uptake, especially at the grower site, where native populations of mycorrhizal fungi may have been suppressed by soil fumigation. However, the effects of inoculation with mycorrhizal fungi were small, and they were more positive in the non-fumigated field at SPRF than in the fumigated field.

Tuber quality

Results for tuber quality characteristics of Ivory Russet grown at the grower site are presented in Table 7. The prevalence of hollow heart and brown center were significantly or marginally significantly related to P rate. This was due to the presence of both flaws in 3% of tubers in the treatment receiving P at a rate of 450 lbs·ac^{-1} P_2O_5 (treatment 5). If P rate truly affects the prevalence of these internal tuber defects, the effect is small and only detectable at very high P rates. The prevalence of scab showed a marginally significant tendency to peak at intermediate P rates of 75 to 300 lbs·ac^{-1} P_2O_5 among the treatments receiving P broadcast before planting without mycorrhizal inoculation (treatments 1-5).

Results for tuber quality characteristics of Russet Burbank grown at the grower site are presented in Table 8. P treatment had no significant effects on tuber quality in this cultivar at this location.

Results for tuber quality characteristics of Ivory Russet grown at SPRF are presented in Table 9. As was true of this cultivar at the grower site, the prevalence of brown center and scab increased marginally significantly with P rate, and this trend largely reflects the highest prevalence occurring at 450 lbs·ac^{-1} P_2O_5 (treatment 5) with a lower prevalence at 300 lbs·ac^{-1} P_2O_5 (treatment 4). The consistency of this result between sites may indicate that very high P rates do increase the risk of hollow heart and brown center in Ivory Russet, which seems to be related to an increase in larger tubers. Specific gravity was marginally significantly related to P treatment, but it was not related to P rate, banded versus broadcast application, or inoculation with mycorrhizae.

Results for tuber quality characteristics of Russet Burbank grown at SPRF are presented in Table 10. The prevalence of hollow heart and brown center increased marginally significantly with P rate, and these increases were seen across the range of P rates tested. There were no other significant effects of treatment on tuber quality in this cultivar at this site.

Overall, a significant or marginally significant positive relationship between P rate and the prevalence of hollow heart and brown center was observed in Ivory Russet at both sites and Russet Burbank at SPRF. This effect was only seen at very high P rates in Ivory Russet, but spanned the full range of P rates tested in Russet Burbank. The prevalence of hollow heart and brown center in Russet Burbank at SPRF was very high overall, and this may explain why the effect of P rate on the prevalence of these defects could be seen at lower P rates. The fact that this effect of P rate was present in three of the four combinations of cultivar and site suggests that, although the effect was not highly significant in any case, it was biologically meaningful. The prevalence of scab was far higher at SPRF than at the grower site in both cultivars. This is probably a result of soil fumigation at the grower site, although differences in cropping history between the two sites may have contributed.

Conclusions

Previous studies at SPRF indicated that Ivory Russet may show a stronger positive yield response to P rate in soils with high test P than Russet Burbank, and this was confirmed by our results, in which total and marketable Ivory Russet yield increased linearly with P rate in both the SPRF and grower fields while total and marketable Russet Burbank yield did not respond significantly to P rate.

Banded application of P fertilizer had no effect on tuber yield at SPRF and a negative effect on total and marketable Ivory Russet yield and the yield of U.S. No. 2 Russet Burbank tubers at the grower site. This is not consistent with potato P uptake being limited by its shallow root system, since banding placed ample P close to the seed tubers.

Tuber yield was neither more nor less responsive to P rate at the grower site, in which the soil was fumigated, than at SPRF, in which it was not. Treating tubers with a product containing mycorrhizal fungi had few effects on yield, and the only positive effects were on the yield of 6- to 10-oz. Russet Burbank tubers and the percentage of yield represented by tubers over 6 oz. at SPRF, in the absence of soil fumigation. Both of these results are inconsistent with P uptake being limited by access to mycorrhizal associates in fumigated fields.

The fact that tuber yield was similarly responsive to P rate in each site also indicates that the differences in Bray P and PSI between the two sites were not consequential in this regard. Application of high rates of P caused significant or marginally significant increases in the prevalence of hollow heart and brown center in Ivory Russet at both sites, as well as Russet Burbank at SPRF. The prevalence of scab was much higher in SPRF, which was not fumigated, than in the grower site, which was fumigated with metam sodium.

Table 1. Treatments applied to both Ivory Russet and Russet Burbank potatoes at both the Sand Plain Research Farm (SPRF) and a nearby grower field.

Treatment	P rate ($lbs \cdot ac^{-1}$ P_2O_5)	Application method	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]MycoGold Potato Blend applied in-furrow at planting with a hand sprayer

Table 2. Soil characteristics in the Sand Plain Research Farm (SPRF) and the grower field in spring, before P fertilizer treatments were applied. MOP and gypsum had been applied to the grower at the time soil samples were taken.

Study field	0 - 6 inches															0 - 2 feet
	Bray P (ppm)	Melich-3 P (ppm)	Melich-3 Al (ppm)	PSI (%)	pH	Organic matter (%)	NH_4OAc-K (ppm)	NH_4OAc-Ca (ppm)	Mehlich-3 Mg (ppm)	Mehlich-3 Mn (ppm)	Mehlich-3 Fe (ppm)	Mehlich-3 Zn (ppm)	Mehlich-3 Cu (ppm)	Hot water B (ppm)	SO_4^{2-}-S (ppm)	NO_3^--N (ppm)
SPRF	126	198	850	23.3	6.6	2.1	160	1201	224	54	171	6.1	2.1	0.3	4	2.6
Grower	95	136	637	21.4	6.4	1.5	432	809	108	50	161	6.1	1.2	0.2	35	4.6

Table 3. Yield, size, and grade of tubers harvested from Ivory Russet potato plants grown at the grower field, where the soil was fumigated with metam sodium in the fall before planting.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total yield	U.S. No. 1 yield	U.S. No. 2 yield	Marketable yield	Percent yield > 6 oz.	Percent yield > 10 oz.
1	0	NA	No	4	17	90	103	68	20 d	298 bc	249	32 e	281 bc	66	32
2	75	Broadcast	No	2	16	81	120	96	37 bcd	350 ab	288	46 cde	334 a	73	39
3	150	Broadcast	No	7	13	71	126	94	57 ab	361 a	273	75 abc	348 a	78	44
4	300	Broadcast	No	2	13	64	120	105	69 a	370 a	261	95 a	357 a	79	47
5	450	Broadcast	No	6	16	75	112	112	68 a	383 a	299	68 abcd	367 a	76	47
6	0	NA	Yes	12	11	60	99	79	39 abcd	288 c	217	60 bcde	277 c	75	41
7	150	Broadcast	Yes	5	12	68	111	99	52 abc	342 ab	248	81 ab	329 ab	77	44
8	75	Banded	No	7	19	78	106	68	30 bcd	300 bc	244	38 de	282 bc	69	35
9	150	Banded	No	3	14	65	111	73	22 cd	285 c	211	60 bcd	271 c	73	34
Treatment effect (P-value)				0.7600	0.5477	0.7618	0.6291	0.1317	**0.0683**	**0.0162**	0.3565	**0.0493**	**0.0123**	0.2838	0.4422
Contrasts (P-values)	Linear P rate (treatments 1-5)			0.7324	0.5738	0.3180	0.8139	**0.0273**	**0.0060**	**0.0179**	0.4011	**0.0198**	**0.0133**	**0.0718**	**0.0539**
	Quadratic P rate (treatments 1-5)			0.8350	0.2669	0.2190	0.1167	0.4022	0.1484	0.2275	0.8732	**0.0172**	0.1704	**0.0516**	0.2783
	Banded v. broadcast (2&3 vs. 8&9)			0.9178	0.5921	0.7455	0.1467	**0.0607**	0.1099	**0.0080**	**0.0644**	0.3946	**0.0058**	0.2100	0.2419
	Mycorrhizae (1&3 vs. 6&7)			0.4399	0.1801	0.1961	0.3572	0.5214	0.5983	0.5009	0.3134	0.2202	0.6072	0.3143	0.4052

Table 4. Yield, size, and grade of tubers harvested from Russet Burbank potato plants grown at the grower field, where the soil was fumigated with metam sodium in the fall before planting.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total yield	U.S. No. 1 yield	U.S. No. 2 yield	Marketable yield	Percent yield > 6 oz.	Percent yield > 10 oz.
1	0	NA	No	1	43	178	169	74	36	500	420	37	457	56	23
2	75	Broadcast	No	1	43	183	181	74	34	516	432	40	472	56	21
3	150	Broadcast	No	1	49	206	167	82	28	532	450	33	483	52	21
4	300	Broadcast	No	1	48	201	181	84	31	546	463	35	497	55	21
5	450	Broadcast	No	0	47	195	173	79	22	516	444	25	469	53	19
6	0	NA	Yes	0	40	200	177	68	20	505	444	21	465	52	17
7	150	Broadcast	Yes	1	53	219	189	75	25	560	477	31	508	52	18
8	75	Banded	No	2	41	178	166	92	34	511	449	21	470	57	25
9	150	Banded	No	1	53	187	155	77	25	496	416	28	444	52	21
Treatment effect (P-value)				0.5581	0.8391	0.6567	0.5804	0.8355	0.7989	0.4367	0.5557	0.1060	0.5388	0.8834	0.8265
Contrasts (P-values)	Linear P rate			0.2229	0.6036	0.3931	0.8303	0.6108	0.2123	0.4821	0.3183	**0.0621**	0.5820	0.4844	0.5723
	Quadratic P rate			0.4948	0.6337	0.3163	0.7571	0.5228	0.9178	0.1637	0.2572	0.5300	0.2041	0.7272	0.9928
	Banded v. broadcast (2&3 vs. 8&9)			0.4506	0.9067	0.4531	0.2396	0.5287	0.8539	0.3505	0.6647	**0.0232**	0.3253	0.9065	0.5670
	Mycorrhizae (1&3 vs. 6&7)			0.3309	0.9578	0.2889	0.1887	0.4886	0.2389	0.4373	0.2406	**0.0891**	0.4401	0.4630	0.1947

Table 5. Yield, size, and grade of tubers harvested from Ivory Russet potato plants grown at SPRF, where the soil was not fumigated.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total yield	U.S. No. 1 yield	U.S. No. 2 yield	Marketable yield	Percent yield > 6 oz.	Percent yield > 10 oz.
1	0	NA	No	3	19	70 bc	72	41	32	233 c	152 bcd	62	214 c	61	31
2	75	Broadcast	No	3	13	61 bcd	71	58	35	237 c	140 cd	84	224 c	69	39
3	150	Broadcast	No	2	13	62 bcd	72	54	27	228 c	131 d	84	215 c	67	36
4	300	Broadcast	No	2	23	69 bcd	82	67	40	281 ab	160 bcd	98	258 ab	67	38
5	450	Broadcast	No	4	25	93 a	91	64	25	298 a	204 a	69	273 a	60	30
6	0	NA	Yes	2	17	57 cd	84	52	20	230 c	142 bcd	71	214 c	68	31
7	150	Broadcast	Yes	1	25	77 ab	75	52	15	245 c	171 b	49	220 c	59	28
8	75	Banded	No	6	15	52 d	79	58	28	232 c	139 cd	78	216 c	71	37
9	150	Banded	No	4	17	64 bcd	74	60	35	252 bc	168 bc	66	234 bc	67	38
		Treatment effect (P-value)		0.8211	0.1964	**0.0311**	0.3962	0.5475	0.1866	**0.0039**	**0.0142**	0.1379	**0.0074**	0.2806	0.3128
Contrasts (P-values)		Linear P rate		0.6597	**0.0508**	**0.0131**	**0.0145**	**0.0511**	0.6411	**<0.0001**	**0.0015**	0.6337	**0.0002**	0.5735	0.6430
		Quadratic P rate		0.3435	0.2302	**0.0396**	0.5437	0.2879	0.3968	0.3940	**0.0171**	**0.0230**	0.5962	**0.0720**	**0.0668**
		Banded v. broadcast (2&3 vs. 8&9)		0.2270	0.3931	0.6623	0.4633	0.6917	0.8641	0.4738	0.1748	0.2792	0.6195	0.8203	0.9755
		Mycorrhizae (1&3 vs. 6&7)		0.7543	0.2114	0.8410	0.2568	0.5568	**0.0736**	0.5847	0.2570	0.2547	0.8579	0.7934	0.3250

Table 6. Yield, size, and grade of tubers harvested from Russet Burbank potato plants grown at SPRF, where the soil was not fumigated.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Culled	0 - 4 oz.	4 - 6 oz.	6 - 10 oz.	10 - 14 oz.	> 14 oz.	Total yield	U.S. No. 1 yield	U.S. No. 2 yield	Marketable yield	Percent yield > 6 oz.	Percent yield > 10 oz.
1	0	NA	No	3	59	150	80 bc	15	2	306	218	28	246	32 c	6 c
2	75	Broadcast	No	6	51	122	110 a	37	12	332	255	26	281	48 a	15 a
3	150	Broadcast	No	4	64	157	68 c	25	4	319	225	29	255	31 c	10 bc
4	300	Broadcast	No	7	54	141	88 b	29	5	317	235	28	263	39 bc	11 b
5	450	Broadcast	No	6	73	141	82 bc	29	6	330	233	24	257	35 bc	10 b
6	0	NA	Yes	5	54	124	90 b	27	7	303	225	23	248	41 ab	11 ab
7	150	Broadcast	Yes	7	62	146	85 bc	27	2	322	236	24	260	36 bc	9 bc
8	75	Banded	No	6	52	119	84 bc	32	4	291	210	29	239	41 ab	12 ab
9	150	Banded	No	7	57	144	96 ab	25	6	329	250	22	271	40 abc	10 b
		Treatment effect (P-value)		0.7876	0.6137	0.3562	**0.0401**	0.1327	0.1187	0.4259	0.2613	0.6176	0.3920	**0.0910**	**0.0638**
Contrasts (P-values)		Linear P rate		0.2800	0.2106	0.9570	0.5458	0.2383	0.9956	0.4555	0.8418	0.4821	0.9901	0.7867	0.4420
		Quadratic P rate		0.5091	0.3359	0.9539	0.9633	0.1272	0.4765	0.8897	0.5399	0.5522	0.4399	0.4489	0.1089
		Banded v. broadcast (2&3 vs. 8&9)		0.5336	0.7128	0.5322	0.8886	0.6162	0.1393	0.2664	0.4086	0.5218	0.3187	0.7982	0.4938
		Mycorrhizae (1&3 vs. 6&7)		0.1456	0.6210	0.1489	**0.0672**	0.1243	0.5772	0.9985	0.4564	0.1107	0.7521	**0.0661**	0.1266

Table 7. Quality characteristics of tubers harvested from Ivory Russet potato plants grown at the grower field, where the soil was fumigated with metam sodium in the fall before planting.

Treatment	P rate ($lbs \cdot ac^{-1}$ P_2O_5)	Application method	Mycorrhizae?	Hollow heart	Brown Center	Scab	Specific gravity	Dry matter content
				---------- % of tubers ----------				%
1	0	NA	No	0	0 b	8	1.0811	21.04
2	75	Broadcast	No	2	1 b	18	1.0814	21.07
3	150	Broadcast	No	0	0 b	17	1.0776	20.60
4	300	Broadcast	No	1	0 b	18	1.0805	21.02
5	450	Broadcast	No	3	3 a	9	1.0782	20.19
6	0	NA	Yes	0	0 b	17	1.0781	20.85
7	150	Broadcast	Yes	0	0 b	13	1.0787	20.15
8	75	Banded	No	0	0 b	14	1.0801	22.11
9	150	Banded	No	0	0 b	25	1.0784	20.96
		Treatment effect (P-value)		0.1713	**0.0673**	0.4683	0.2767	0.2578
Contrasts (P-values)		Linear P rate		**0.0574**	**0.0158**	0.8447	0.1506	0.2699
		Quadratic P rate		0.3704	**0.0538**	**0.0818**	0.7076	0.6743
		Banded v. broadcast (2&3 vs. 8&9)		0.2668	0.4739	0.6873	0.8719	0.1685
		Mycorrhizae (1&3 vs. 6&7)		1.0000	1.0000	0.6885	0.4617	0.5255

Table 8. Quality characteristics of tubers harvested from Russet Burbank potato plants grown at the grower field, where the soil was fumigated with metam sodium in the fall before planting.

Treatment	P rate ($lbs \cdot ac^{-1}$ P_2O_5)	Application method	Mycorrhizae?	Hollow heart	Brown Center	Scab	Specific gravity	Dry matter content
				---------- % of tubers ----------				%
1	0	NA	No	4	4	1	1.0769	19.80
2	75	Broadcast	No	0	0	3	1.0792	20.45
3	150	Broadcast	No	4	1	1	1.0782	20.28
4	300	Broadcast	No	4	3	0	1.0771	20.40
5	450	Broadcast	No	3	2	1	1.0803	20.12
6	0	NA	Yes	1	1	3	1.0795	20.31
7	150	Broadcast	Yes	3	2	1	1.0785	20.12
8	75	Banded	No	3	2	1	1.0795	20.23
9	150	Banded	No	2	2	1	1.0786	20.41
		Treatment effect (P-value)		0.3666	0.5554	0.4259	0.6570	0.9860
Contrasts (P-values)		Linear P rate		0.6193	0.9842	0.3424	0.2428	0.7726
		Quadratic P rate		0.8624	0.3511	0.7598	0.5518	0.3582
		Banded v. broadcast (2&3 vs. 8&9)		0.7118	0.2466	0.3177	0.7722	0.9146
		Mycorrhizae (1&3 vs. 6&7)		0.1479	0.4363	0.3073	0.2685	0.6885

Table 9. Quality characteristics of tubers harvested from Ivory Russet potato plants grown at SPRF, where the soil was not fumigated.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Hollow heart	Brown Center	Scab	Specific gravity	Dry matter content
				---------- % of tubers ----------				%
1	0	NA	No	2	2	71	1.0712 abc	19.70
2	75	Broadcast	No	0	0	89	1.0676 cd	19.65
3	150	Broadcast	No	0	0	95	1.0682 cd	19.39
4	300	Broadcast	No	3	2	61	1.0738 ab	20.59
5	450	Broadcast	No	6	6	73	1.0714 abc	20.10
6	0	NA	Yes	0	1	71	1.0706 abcd	20.33
7	150	Broadcast	Yes	1	2	71	1.0697 bcd	20.03
8	75	Banded	No	0	0	96	1.0662 d	19.29
9	150	Banded	No	2	2	67	1.0746 a	21.26
Treatment effect (P-value)				0.4613	0.5670	0.2443	**0.0842**	0.6993
Contrasts (P-values)	Linear P rate			**0.0542**	**0.0752**	0.3655	0.2260	0.4386
	Quadratic P rate			0.2031	0.1411	0.5216	0.7634	0.9106
	Banded v. broadcast (2&3 vs. 8&9)			0.6345	0.6388	0.3396	0.2128	0.3264
	Mycorrhizae (1&3 vs. 6&7)			0.8118	0.8142	0.2725	0.8188	0.4062

Table 10. Quality characteristics of tubers harvested from Russet Burbank potato plants grown at SPRF, where the soil was not fumigated.

Treatment	P rate (lbs·ac^{-1} P_2O_5)	Application method	Mycorrhizae?	Hollow heart	Brown Center	Scab	Specific gravity	Dry matter content
				---------- % of tubers ----------				%
1	0	NA	No	17	15	69	1.0617	18.36
2	75	Broadcast	No	18	17	82	1.0619	17.34
3	150	Broadcast	No	21	17	64	1.0615	17.90
4	300	Broadcast	No	22	20	89	1.0623	18.85
5	450	Broadcast	No	25	24	67	1.0605	18.32
6	0	NA	Yes	17	16	79	1.0628	17.85
7	150	Broadcast	Yes	17	11	80	1.0631	18.18
8	75	Banded	No	18	15	64	1.0626	17.37
9	150	Banded	No	16	15	77	1.0644	18.58
Treatment effect (P-value)				0.5075	0.4662	0.4343	0.3826	0.1283
Contrasts (P-values)	Linear P rate			**0.0572**	**0.0612**	0.9552	0.4786	0.1980
	Quadratic P rate			0.9199	0.7908	0.2736	0.4203	0.9127
	Banded v. broadcast (2&3 vs. 8&9)			0.4112	0.5609	0.7663	0.1173	0.3642
	Mycorrhizae (1&3 vs. 6&7)			0.4795	0.5191	0.1501	0.1918	0.7592