

Grafted Tomatoes Removed More Soil Phosphorus than Nongrafted Tomatoes under High-phosphorus Conditions

Charlie L. Rohwer

University of Minnesota Southern Research and Outreach Center, 35838
120th St., Waseca, MN 56093, USA

Keywords. Estamino, fish emulsion, rootstock, *Solanum lycopersicum*, starter fertilizer

Abstract. Nonpoint-source phosphorus (P) from agricultural fields is a contaminant of surface waters, and high soil P fertility exacerbates this problem. Many vegetable growers and gardeners have a history of applying more P than is necessary for optimum plant growth. Avoiding unnecessary P applications is an important part of the long-term solution to reducing P loading in water. When soil P levels are very high, management practices that result in more intense P removal are recommended to reduce these levels and the potential for aquatic ecosystem contamination with P. Growers may apply soluble starter fertilizer containing P to encourage rapid transplant establishment; however, the effectiveness of this practice is unknown for soil P levels considered high or very high. Grafting tomatoes (*Solanum lycopersicum* L.) onto vigorous rootstocks may help the plant remove more P from the soil than nongrafted plants. This study investigated the effects of organic starter P fertilizers applied to three hybrids of nongrafted tomato and the same hybrids grafted onto ‘Estamino’ rootstock in field-grown conditions during three site-years with high preplant P fertility. The yield, fruit P concentration, and amount of P removed from the field were measured to elucidate starter P and grafting impacts on P removal. Starter P was not impactful on all responses. Grafting increased the total yield by 11.6%, fruit P concentration in a genotype-dependent manner (average of 12.6%), and net P removal from the field by 28.4% (6.0 kg P/ha). Net P removal was positively correlated with the total yield ($r = 0.821$) and fruit P concentration ($r = 0.502$), suggesting that practices to increase the yield or P concentration independently increase net P removal.

Vegetable growers and gardeners may apply more phosphorus (P) than is needed for their crops, especially through repeated applications of manure and compost (Rosen and Bierman 2005; Small et al. 2019b). Applications of “balanced” fertilizers (10N–4.3P–8.3K, for example) to meet nitrogen (N) needs may also cause soil P accumulation. In 2017, researchers in Pennsylvania found that in 27 soil samples from high tunnels, all but one contained enough P to “exceed crop needs,” and that the average of 1359 soil samples from vegetable fields was 2.3-times higher than the minimum required to “exceed crop needs” (Sánchez and Ford 2023). A 2023 survey of high tunnels and adjacent fields on Minnesota farms found that 161 of 200 soil samples had “very high” P (Natalie Hoidal, personal

communication). A survey of urban agriculture in Minnesota found that 75% of soils contained more than 58.3 mg/kg according to the Bray P test (Small et al. 2019b). At this soil level, the only vegetable crops recommended to receive additional P are potatoes or new plantings of asparagus or rhubarb (Rosen and Eliason 2005). Imbalances between fertilizer P use and plant needs are not problems unique to midwestern United States gardeners and vegetable farmers (MacDonald et al. 2011; Yan et al. 2013).

Excess soil P typically does not result in toxicity to crops (Lambers 2022). The primary concern with excess soil P is its impact on water quality and eutrophication. Managing the agricultural impact on eutrophication requires managing P and N losses from soil (Carpenter 2008; Conley et al. 2009). Phosphorus loss from soil can occur via leaching of dissolved P, surface runoff, or erosion. Generally, soils with higher P are at higher risk for P loss, especially in coarse-texture or P-saturated soil (Duncan et al. 2017; Hussain et al. 2021; Kalkhajeh et al. 2017; Sharpley et al. 2013; Tian et al. 2022).

The excess P accumulated over time in the soil, including by the addition of fertilizers and amendments, is referred to as “legacy P.” Over time, the removal of legacy P through harvested plant material (P drawdown) can reduce very high soil P to moderate levels if appropriate fertilization is practiced (Rowe et al. 2016; Withers et al. 2014). However, if unnecessary P

applications continue, then legacy P and potential P loss to the environment increase. For example, the overall average P removal from field-grown produce according to 28 studies in China was 25 kg P/ha, but an average of 92 kg P/ha was applied in excess (Yan et al. 2013). Others measured excess P applications up to >2000 kg P/ha per year (Tian et al. 2022). If mechanisms can be developed to help crops, such as tomatoes (*Solanum lycopersicum* L.), remove additional soil P through increased yield and increased P concentrations in harvested plant materials, then farmers and gardeners could work toward more rapid P drawdown, especially when legacy P is used as a primary P source (Tian et al. 2022).

When transplanting vegetables, applying a soluble fertilizer (“starter fertilizer”) with a low N:P ratio is commonly recommended to encourage rapid establishment of transplants. Previous research performed in Minnesota indicated that applying high-P starter fertilizer at transplant can improve tomato yield, even when soil tests indicate moderate to high P levels; for example, 5.8 kg P/ha was effective as starter fertilizer according to a previous study (Rohwer and Fritz 2016). It remains unclear whether the amount of soluble P fertilizer added at transplant is subsequently removed from the field at harvest (as a tomato fruit constituent), or whether more (or less) P was removed than was added to the soil with the soluble fertilizer.

In addition, methods to enhance yield without adding additional P would be useful to remove extra P from the soil. Grafting tomatoes onto vigorous rootstocks may be one way to accomplish this. For example, the P concentration in ‘Ikram’ tomato fruit was not impacted by grafting onto ‘Unifort’ or ‘Maxifort’ rootstock hybrids (*S. lycopersicum* × *S. habrochaites* S. Knapp & D.M. Spooner), but the total yield was increased (Kumar et al. 2015). Other studies have found both increased yield and fruit P concentration (Gong et al. 2022a, 2022b; Ruiz et al. 1997). More root hairs, greater root density in soil, higher specific root length (m/g), smaller root diameter, and greater total root length were observed in tomatoes grafted onto ‘Beaufort’ rootstock (Oztekin et al. 2009; Suchoff et al. 2018). In general, rootstocks can provide a better ability to uptake minerals or explore more soil, especially under deficiency conditions (Nawaz et al. 2016; Savvas et al. 2010). These findings suggest that an increase in P removal from soil is possible through grafting, but it has not specifically been studied under high-P fertility.

To understand these relationships between grafting and soluble transplant fertilizers and their ability to remove P from the soil through harvested tomato yield, this study evaluated the P concentration and yield of tomatoes under conditions of excess P fertility. It was hypothesized that starter fertilizers would not increase tomato yield and would not change the fruit P concentration; therefore, another hypothesis was that starter fertilizers would contribute to P accumulation in soil. Other hypotheses were that grafting tomatoes onto

Received for publication 18 Dec 2023. Accepted for publication 10 Jan 2024.

Published online 29 Feb 2024.

I thank Dan Zimmerli and the staff at Cedar Crate Farm for plot preparation and maintenance. I also thank two anonymous reviewers for helpful suggestions. This research was funded by an Agricultural Growth, Research, and Innovation (AGRI) Sustainable Agriculture Demonstration Grant from the Minnesota Department of Agriculture (MDA).

C.L.R. is the corresponding author. E-mail: rohwer0009@umn.edu.

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a commercial rootstock ('Estamino') would lead to increased yield, no change in the fruit P concentration, and additional P removed from the soil compared with that of non-grafted plants. These hypotheses were tested using a replicated split-plot design at two locations during two years.

Materials and Methods

Field design and treatments. The experiment was performed at two locations: Cedar Crate Farm (CCF) (Waldorf, MN, USA; lat. 43.9053°N, long. 93.6785°W) and the University of Minnesota Southern Research and Outreach Center (SROC) (Waseca, MN, USA; lat. 44.0760°N, long. 93.5233°W). The soil type at both locations is a Webster clay loam (mesic endoaquoll), with a recent history of organic practices at CCF and conventional management at SROC. The previous crops were soybeans [*Glycine max* (L.) Merr.] in 2021 and wheat (*Triticum aestivum* L.) in 2022 at SROC, and *Cucurbita* species at CCF in both years. The specific field was different in each year at SROC, which is why preplant soil test results were different each year (Table 1). An additional site-year (CCF 2022) was not included because plants succumbed to disease. The total yield from CCF 2022 was 50% of the three site-years included, and average fruit size was 43% smaller. Precipitation and temperature are detailed in Supplemental Table 1. All seedlings were grown at a commercial greenhouse (Grafted Growers, Raleigh, NC, USA). Scions were 'Galahad' and 'Mountain Fresh Plus' (2021, 2022), 'Paisano' (2021 only), and 'Plum Regal' (2022 only), which were chosen by D. Zimmerli (CCF) for commercial use and purchased commercially (all seed from Johnny's Selected Seeds, Winslow, ME, USA). The rootstock for grafted treatments was 'Estamino', which was chosen because it performed well during a recent trial in Iowa (Lang et al. 2020). Seedlings were received in 128-cell trays on 19 May 2021 or 12 May 2022; grafted and non-grafted plants were similar in size. Seedlings were moved to 72-cell trays after receipt in 2022. Plants were hardened-off in a high tunnel in Waseca and then transplanted at root-ball level in 2021 on 2 Jun (CCF) or 21 May (SROC), and in 2022 on 27 May. Between-row spacing distances were 1.2 m at CCF and 1.5 m at SROC, and within-row spacing distances were 0.6 m at CCF (single row) and 0.5 m at SROC (double row, staggered). At both locations, there were 13,455 plants/ha. The CCF location was entirely covered by weed barrier fabric with holes for planting, and the SROC location used raised beds covered with biodegradable plastic mulch (BioTelo; Jordan Seeds, Woodbury MN, USA). Preplant fertilizer additions are shown in Table 1 were based on soil test results and recommendations at SROC (Rosen and Eliason 2005) and the annual broadcast rate used by CCF. Preplant P fertilizer exceeded recommendations by 12 kg P/ha at CCF and 37 kg P/ha at SROC. This was to approximate excess soil P to evaluate starter fertilizer treatments under high-P conditions. Organic starter fertilizers (based

Table 1. Preplant soil test results and fertilizer used at Cedar Crate Farm (CCF) and the Southern Research and Outreach Center (SROC) in 2021 and 2022. CCF had a history of organic fertilization but SROC did not.

Soil parameter	CCF	SROC	
	2021	2021	2022
pH	7.2	6.6	5.7
OM (%) ⁱ	5.7	5.8	4.8
P (mg/kg) ⁱⁱ	36	37	17
K (mg/kg) ⁱⁱⁱ	169	144	128
Preplant fertilizer added (kg/ha)			
4N-1.3P-1.7K ^{iv}	2803	0	2809
8N-0.9P-3.3K ^v	0	2453	1404
0N-20.1P-0K	0	198	183
0N-0P-18.3K	0	67	0
Preplant nutrients from fertilizer (kg/ha)			
N	112	196	225
P	37	61	86
K	47	94	93

ⁱ Organic matter.

ⁱⁱ Extractable P according to the Bray test.

ⁱⁱⁱ NH₄OAc-extractable K.

^{iv} Agricultural Innovations, Winthrop, MN, USA. Organic nitrogen (N) sources were composted poultry litter and feather meal.

^v Sustane, Cannon Falls, MN, USA. Organic N sources were composted poultry litter and feather meal.

on fish hydrolysate) (Table 2) were applied as a 237-mL volume per plant immediately after transplanting. Plants were supported by a stake-and-weave system and drip-irrigated as needed.

Plots were arranged in a split-plot design at each location, with three replicates per location. The whole-plot factor was tomato hybrid, and the sub-plot factor was one of the following five treatments: control (not grafted, no starter fertilizer); low-P not grafted; high-P not grafted; low-P grafted; or high-P grafted. 'High' P rates in 2021 were based on previous research using mineral starter fertilizer in soil with adequate fertility (Rohwer and Fritz 2016). Starter P rates were lower in 2022, reflecting either a label recommendation of 7.8 mL/L or a dilution rate similar to that used in 2021 (58.6 mL/L) (Table 2). Each sub-plot consisted of three plants; at each site-year, there were 45 plots and 135 total plants. Fruits were only harvested from the middle plant in each plot. Fruits were harvested if they were turning, pink, light red, or red at least weekly, and the calyx and stem were removed from all fruits at harvest. At the final harvest, all remaining fruits were harvested, including the unripe. At each harvest, marketable (minimal damage, physiological disorders, or disease) and unmarketable fruits were counted and weighed separately.

Processing for P analysis. At each harvest, two to four representative fruits (marketable, unmarketable, and/or green) were placed in a plastic bag and stored at 34 °C until processing could commence. The reason for including all fruits, not just marketable fruits, is that unmarketable and green fruits are typically removed from the field. The contents of each bag were blended in a kitchen blender; then, a subsample was frozen and stored in a 50-mL plastic sample vial. After all harvests were completed, the frozen samples were thawed and mixed by volume proportional to the total weight from

each individual harvest to create a mixed sample from each plot totaling 35 mL. For example, if one plot was harvested three times, with 1, 2, and 4 kg per harvest, then the mixed sample would contain 5, 10, and 20 mL blended samples from the respective harvests. This 35-mL blend was then homogenized using a Polytron PT 1300 D (Kinematica, Inc., Bohemia, NY, USA). The homogenized sample was added to a weighed porcelain crucible with a lid and then dried in an oven at 70 °C for 1 week. The crucible was weighed after drying, and the dried sample was ground in a mortar and pestle before submitting to the University of Minnesota Research Analytical Laboratory for a multielement inductively coupled plasma analysis (dry ash). The fruit moisture content was calculated from the fresh and dry weights of the blended sample. The amount of P removed from the soil per plant was calculated from the calculated total fruit dry weight harvested per plant, percent moisture in fruit, and measured fruit P concentration (mg P/g dry weight). Net P removed from the soil by fruit harvest (kg P/ha) was calculated by subtracting the P added by the starter fertilizer (Table 2) from the total P in harvested fruit.

Statistics. Cumulative marketable tomato yield (Mg/ha) data were subjected to a mixed-

Table 2. Transplant fertilizer solutions used in 2021 and 2022, and nitrogen (N) and phosphorus (P) provided. Each plant received 237 mL solution at transplant, and there were 13,450 plants per ha.

kg P/ha	Yr	Fertilizer	mL/L	kg N/ha
0.0	2021, 2022	Water only		0.0
0.37	2021	5N-0.4P-0.8K ⁱ	23.4	4.3
3.7	2021	2N-1.7P-0.8K ⁱⁱ	58.6	4.3
0.1	2022	5N-0.4P-0.8K ⁱ	7.8	1.4
0.9	2022	5N-0.4P-0.8K ⁱ	57.4	10.5

ⁱ Aqua Power 5-1-1; JH Biotech, Ventura, CA, USA.

ⁱⁱ Neptune's Harvest 2-4-1; Neptune's Harvest, Gloucester, MA, USA.

model analysis of variance (ANOVA) using the lme4 package in R (Bates et al. 2015; R Core Team 2023). Fixed effects included hybrid ($n = 3$), site-year ($n = 3$), and grafting ($n = 2$); the linear effect of the response to the starter fertilizer P application rate was included, and the interactions of all four effects were modeled. The P rate was modeled instead of the N rate because of the marginally better R^2 from simple linear models (Supplemental Fig. 1). The hybrid was nested within the year $\times$ location $\times$ replicate random effect to account for the split-plot design. This model was also used to study fruit size, P concentration, and net P removal/ha. Wald χ^2 tests were used to determine the significance of main effects and interactions (car::Anova) (Fox and Weisberg 2019). Marketable yield data were ln-transformed before the analysis, and the P concentration and P removal data were square-root-transformed to account for heteroskedasticity.

For all analyses, the ‘Paisano’ hybrid grown in 2021 and ‘Plum Regal’ hybrid grown in 2022 were included as a single “paste” hybrid because there were no apparent differences between the two. For all ANOVAs, if type III P values for main effect interactions were >0.1 , then they were removed, and the simplified model was confirmed as no worse than the full model with a log-likelihood ratio test (nested ANOVA; $\alpha = 0.1$) and a reduction in the Akaike information criterion.

Marginal means were determined using emmeans::emmeans (Lenth 2023). Effects sizes were calculated as the confidence interval (CI) of the contrast estimate using Kenward-Rogers estimates for degrees of freedom. The CIs and marginal means were back-transformed. For standardized measures of the effect size of grafting on yield, P concentration, and P removal, independent of modeling, Vargha and Delaney’s A was calculated because it is simple to interpret in a variety of contexts and is useful for meta-analyses (Peng and Chen 2014; Vargha and Delaney 2000). To calculate A (effectsize::vd_a) (Ben-Shachar et al. 2020), average data were paired within hybrids, replicates, and site-years ($n = 27$ for nongrafted or grafted).

Results and Discussion

Fruit yield. The average total fruit yield was 114 Mg/ha (median = 108), and the average marketable yield was 97 Mg/ha (median = 93) (Supplemental Fig. 2). Harvest occurred 72 to 139 d after transplant in 2021 (ended 7 Oct) and 68 to 117 d after transplant in 2022 (ended 21 Sep). To reduce the potential for a type I error, and because marketable and total yields were strongly correlated (Supplemental Fig. 2), contrasts between treatments for total yield are not shown. The marketable yield varied because of the site-year (Table 3) and was highest at CCF 2021 (108 Mg/ha) (Fig. 1). The lower yield at SROC 2022 (79 Mg/ha) could be attributable to the harvest ending earlier in 2022 because of forecasted frost (Supplemental Table 1).

There were minor differences in yield among the hybrids studied (Table 3, Fig. 1).

Table 3. P values for type III Wald χ^2 tests of significance from the analysis of variance with associated degrees of freedom (df). Net phosphorus (P) removed from the field via harvest was calculated from the tomato yield and fruit P concentration. Interactions with $P > 0.05$ were removed from models with no impact on model quality.

Modeled effect	df	Marketable tomato yield (Mg/ha)	Fruit P concn (mg P/100 gfw)	Net P removed (kg P/ha)
SY	2	0.001	<0.001	<0.001
H	2	0.057	<0.001	<0.001
Starter P fertilizer (linear)	1	0.973	0.315	0.050
G	1	0.028	<0.001	<0.001
H $\times$ G	2		0.042	
SY $\times$ H	4			0.009

G = grafting; H = hybrid; SY = site-year.

‘Mountain Fresh Plus’ (‘Mtn. Fresh Plus’) yielded the most (104 Mg/ha; 95% CI: 93–118), but this was not significantly different from that of the other hybrids (Fig. 1). The size of marketable fruit, however, was impacted by both site-year and hybrid. For example, the average fruit size of ‘Mtn. Fresh Plus’ was 198 g across all site-years, but ‘Galahad’ fruits were largest at SROC in 2022 (216 g), and the paste hybrids were smallest at CCF in 2021 (62 g) (Table 4). Our results suggest that the ‘Mtn. Fresh Plus’ fruit size is dominated more by genotype than by environment compared with the other hybrids.

Starter fertilizer had no impact on yield (Table 3, Supplemental Fig. 1). Treating starter fertilizer as a fixed effect in the ANOVA resulted in similar conclusions (not shown). Previous experience applying 5.8 kg P/ha in starter fertilizer to ‘Plum Dandy’ tomatoes at SROC indicated that an approximately 18% yield increase could be expected (Rohwer and Fritz 2016). However, fertilizer in the current study, unlike that in the previous study, was from organic sources. When 50 mg P from fish hydrolysate was added per gram of soil to two different soils and incubated at 10 °C for 3 d, the measured P content of the soil increased by 12.5 to 20 mg (Zhang et al. 2007). Starter fertilizer P in the current study could have been ineffective at increasing yield because of the low application rate, low availability, or low plant need because of high soil P. Excess P fertilizer additions were intended to mimic soil high in P. In 2022, for instance, the Bray P test result was 17 mg/kg, which is fairly low for tomato needs. The recommended P fertilizer rate for tomatoes at this soil level is 49 kg/ha (Rosen and Eliason 2005). The total P applied at this site-year was 86 kg P/ha, with 37 kg P as inorganic 0N–20.1P–0K and 49 kg P from composted poultry litter (Table 1). The initial P release (and soil availability) from composted poultry litter and organic amendments can be fairly rapid (Cooperband et al. 2002; Prasad et al. 2004; Preusch et al. 2002), and organic P sources may be more available for plants throughout the season than inorganic P because of less P adsorption to soil or P mineralization better-timed to the crop needs (Sikora and Enkiri 2003). Even so, it is likely that inorganic starter fertilizer (as in the 2016 study) would be even more rapidly available than organic forms at transplant (as in the current study);

however, direct comparisons of the effects of organic and conventional soluble starter fertilizers on transplanted crop productivity or P uptake, especially in high-P conditions, are unknown.

Grafting had a small positive impact on yield (Table 3). The mean yield from non-grafted plants was 88, and the yield from grafted plants was 98 Mg/ha. The average increase in yield attributable to grafting was 11.6% (95% CI: 1.2% to 23.1%) (Fig. 1). To emphasize the magnitude, direction, and uncertainty of the grafting effect on yield, Vargha and Delaney’s A for grafting was 0.7 (95% CI: 0.49–0.85). The interpretation of this is

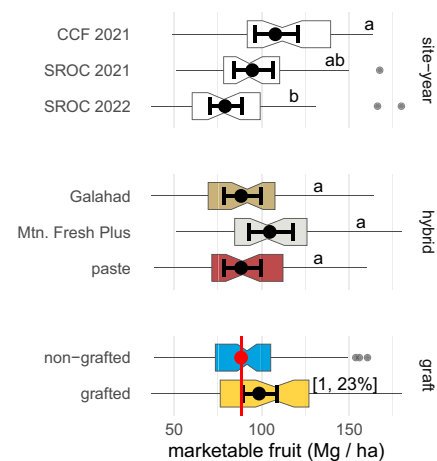


Fig. 1. Marketable tomato fruit from three site-years ($n = 45$ per site-year), three hybrids ($n = 45$ per hybrid), and two grafting treatments (nongrafted, $n = 81$; grafted, $n = 54$). Boxplots illustrate raw data. The box width is the interquartile range (IQR; first to third quartiles), and whiskers extend from the box to the largest value no further from the IQR than 1.5-times the IQR. Outliers (included in the analysis of variance) are shown beyond whiskers. Notches in boxplots illustrate a model-independent confidence interval (CI) of the median ($1.58 \times \text{IQR}/\sqrt{n}$). Marginal means are shown as circles within the IQR. Error bars for site-year and hybrid represent the 95% CI of the marginal mean. Lowercase letters indicate differences based on Tukey’s honest significant difference (HSD) ($\alpha = 0.05$). The red line in the “graft” plot indicates the mean of the nongrafted treatment, and the error bar is the 95% CI of the contrast between grafted and nongrafted. The relative response to grafting (% of nongrafted, 95% CI) is shown in brackets.

Table 4. Tomato fruit size (grams per marketable fruit) for three hybrids ('Galahad', 'Mtn. Fresh Plus', or paste hybrids) that were nongrafted or grafted onto 'Estamino' rootstocks averaged over three site-years. Data from three site-years [Cedar Crate Farm (CCF) 2021, Southern Research and Outreach Center (SROC) 2021, or SROC 2022] are included for hybrids as well and averaged over the grafting treatment. Hybrids were analyzed using separate analyses of variance. *P* values for contrasts between grafting treatments are shown, and letters within hybrids indicate significant differences between site-years based on Tukey's honest significant difference (HSD) ($\alpha = 0.05$).

Hybrid	g per fruit		<i>P</i>	g per fruit		
	Nongrafted	Grafted		CCF 2021	SROC 2021	SROC 2022
Galahad	182	194	0.041	182 b	216 a	166 b
Mtn. Fresh Plus	198	198	0.982	193 a	209 a	192 a
Paste	77	80	0.116	62 b	85 a	89 a

that a random sample of yield from grafted plants would be larger than a random sample of yield from nongrafted plants 70% of the time (95% CI: 49% to 85% of the time). Furthermore, $A = 0.5$ would indicate no treatment effect, and $A = 1.0$ would indicate a positive treatment effect so strong that the chance of no positive effect is zero. The uncertainty of these results (95% CI) suggests that although the direction of the grafting response is likely positive, it is not extremely reliable. A recent study in Nebraska found that delayed maturity of field-grown tomatoes grafted onto 'Estamino' rootstock contributed to a lack of yield benefit from grafting (Shonerd et al. 2023). However, grafting was shown to enhance establishment and support growth through improved nutrient and water relations compared with nongrafted plants during another field study (Bristow et al. 2021). It should be noted that many tomato grafting experiments are performed in high tunnels, where late-season growth is under warmer temperatures than is possible outdoors in southern Minnesota, and any delay in maturity caused by grafting may be less critical.

In our study, grafting marginally increased the fruit size of only 'Galahad' (Table 4) (95% CI: 0.3% to 12.4% increased size); generally, size was not substantially different because of grafting of any scion. Another study found fruits from scions grafted to 'Estamino' were 3% to 5% larger, on average, than fruits from nongrafted plants, but the difference was not considered significant (Djidonou et al. 2020). 'Estamino' rootstock increased the marketable yield of greenhouse-grown 'BHN 1022', 'Skyway', and 'Sweet Hearts' tomato by an average of 10% to 122% through an increase in the total fruit number rather than that in the fruit size (Gong et al. 2022a). However, one study found that the total yield was increased in greenhouse-grown 'BHN 589' grafted onto 'Estamino' by an average of 61% to 121%, partly because of a >25% increase in fruit size (Lang et al. 2020). Increased fruit weight was partially responsible for the increased yield of grafted tomatoes in a Florida field trial (Djidonou et al. 2016). Generally, the fruit size or number may increase because of grafting, depending on specific rootstock and scion properties (Kyriacou et al. 2017; Lang et al. 2020; Mauro et al. 2020).

Fruit P concentration. The fruit P concentration was strongly impacted by site-year (Table 3). Similar to yield, fruit from SROC 2022 had the lowest P concentration, and

fruit from CCF 2021 had the highest (19.8 or 25.2 mg P/100 gfw, respectively) (Fig. 2). The raw mean P concentrations were 25.2, 21.6, and 21.0 mg P/100 gfw for 'Galahad', 'Mtn. Fresh Plus', and paste tomatoes, respectively (*SD*: ± 5.3 , 3.6, and 3.4, respectively). The percent moisture was lowest in 'Galahad' (94.7%) and highest in the paste hybrids (95.4%). However, the P concentration based on dry weight is not reported here because the fresh tomato yield is measured based on fresh weight, and because net P removal is not impacted by fruit moisture. Grafting had the greatest impact on the P concentration in 'Galahad' (22% increase), with smaller increases caused by grafting in the other hybrids (Fig. 2). Independent of the ANOVA model, Vargha and Delaney's $A = 0.9$ for grafting effects on the fruit P concentration (95% CI: 0.79–0.95). This leaves no doubt that grafting increased the fruit P concentration overall in our study. From marginal means, grafting increased the average fruit P concentration from 21.0 to 23.7 mg P/100 gfw (+12.6%).

Both a higher yield and an equal or higher P concentration seem to be common responses to grafting. During peak harvest, grafting tomatoes onto 'Estamino' rootstock generated fruits with equal or greater macronutrient and micronutrient concentrations compared with nongrafted plants, including 10% to 40% more P, and increased yield (Gong et al. 2022a, 2022b). 'Rita' tomato grafted onto 'Beaufort' tomato rootstock had 35% more marketable yield and no difference in fruit P concentration compared with self-grafted. Conversely, eggplant (*Solanum melongena* L.) yield was 23% lower with a 207% higher P concentration when grafted to 'Beaufort' rootstock (Leonardi and Giuffrida 2006). This was not true for P during one study in which the yield increase was not associated with any change in the P concentration of eggplant grafted onto *Solanum torvum* 'Espina' rootstock, and grafting effects on other mineral concentrations were variable (Mauro et al. 2022). Generally, grafted watermelons were shown to have higher yield and variable but higher fruit P concentrations than nongrafted or self-grafted plants (Jordana et al. 2023).

The lack of correlation between the fruit P concentration and fruit yield ($r = -0.013$; $P = 0.88$) (Fig. 3, Supplemental Fig. 3) suggested no evidence of nutrient dilution for

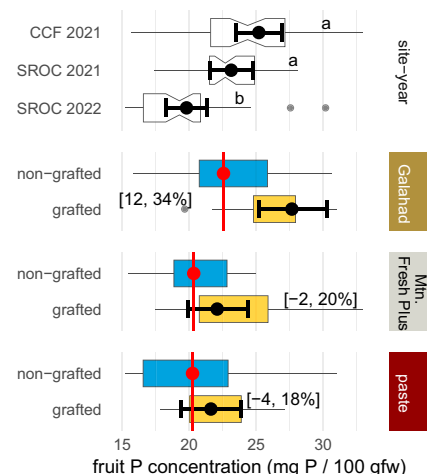


Fig. 2. Tomato fruit phosphorus (P) concentration from three site-years ($n = 45$ per site-year) and grafting treatments within three hybrids ($n = 27$ per nongrafted treatment within hybrid; $n = 18$ per grafted treatment within hybrid). Boxplots illustrate raw data. The box width is the interquartile range (IQR; first to third quartiles), and whiskers extend from the box to the largest value no further from the IQR than 1.5-times the IQR. Outliers (included in the analysis of variance) are shown beyond whiskers. Notches in boxplots illustrate a model-independent confidence interval (CI) of the median ($1.58 \times \text{IQR}/\sqrt{n}$). A lack of notches indicates that notches extend beyond the IQR. Marginal means are shown as circles within the IQR. Error bars for site-year represent the 95% CI of the marginal mean. Lowercase letters indicate differences based on Tukey's honest significant difference (HSD) ($\alpha = 0.05$). The red line in the hybrid plots indicates the mean of the nongrafted treatment, and the error bar is the 95% CI of the contrast between grafted and nongrafted. The relative response to grafting (% of nongrafted, 95% CI) is shown in brackets.

P, whereby lower yields are associated with higher mineral contents (Davis 2009). The relationship within grafted plants only ($r = -0.295$; $P = 0.030$) was influenced by two 'Galahad' plots with P concentrations >40 mg P/100 gfw (Fig. 3).

The starter P rate did not influence the fruit P concentration (Table 3). Treating the starter P rate as a categorical factor resulted in the same conclusion (not shown). A simple linear model showed a possible slight increase in the fruit P concentration attributable to the starter P rate, but this is far from conclusive ($R^2 = 0.07$) (Supplemental Fig. 1). Nonresponsiveness to starter P could be caused by the same factors previously described for nonresponsiveness to yield.

Net P removal. The amount of P added by the starter fertilizer was subtracted from the measured P removed before the statistical analysis to calculate net P removal. Therefore, if the calculated net P removal was negative because of a treatment effect (starter P or grafting), then that would indicate that P likely accumulates in the soil because of the treatment. Similar to yield and fruit P concentration responses, the ANOVA and a simple

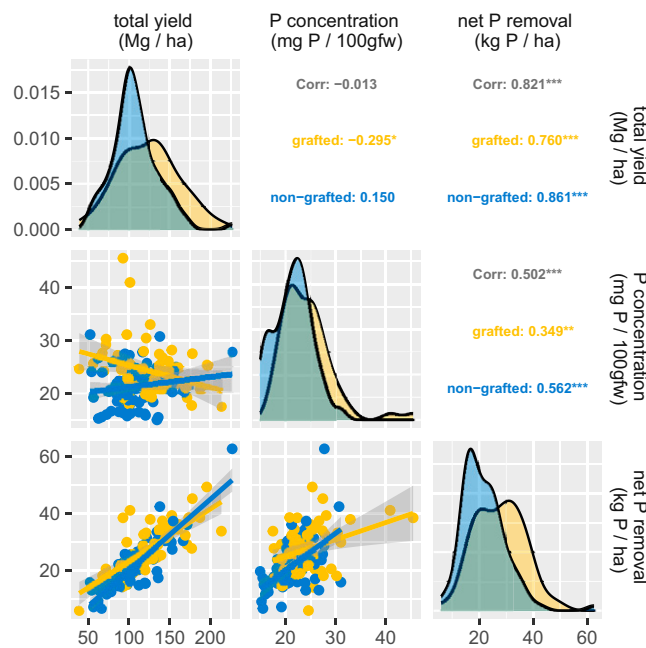


Fig. 3. Correlations between total tomato yield (Mg/ha), tomato fruit phosphorus (P) concentration (mg P/100 gfw), and net P removal by tomato harvest (kg P/ha). The X-axes indicate values for these responses (Mg/ha, mg/100 gfw, or kg/ha). Plots on the diagonal are probability density plots of raw data (y axis = probability) for nongrafted or grafted plants ('Estamino' rootstock). Raw data and trend lines for the relationship between pairs of responses for grafted or nongrafted plants are shown below density plots. Pearson's correlation coefficients for the responses using all data (overall) or data within nongrafted or grafted are shown above density plots. *, **, ***Correlations are significant at $\alpha = 0.05$, 0.01, or 0.001, respectively.

linear model suggested no impact of starter P on net P removal ($P = 0.05$ and $P = 0.35$, respectively) (Table 3, Supplemental Fig. 1). Treating starter P as a fixed effect or bootstrapping raw data for measuring treatment effects similarly found no effect of starter P on the net P removed (not shown).

The overall average net P removal during our study was 24.1 kg P/ha. This is a reasonable number because the US Department of Agriculture reports that roma tomatoes contain ~20 mg P/100 gfw (similar to our measurements) (US Department of Agriculture, Agricultural Research Service 2021). At a yield of 100 Mg/ha (US Department of Agriculture, National Agricultural Statistics Service 2021), harvesting tomato fruit would remove 20 kg P/ha from the soil.

Net P removal was lowest overall in the paste hybrids (21.7 kg P/ha) and marginally higher in 'Mtn. Fresh Plus' and 'Galahad' (24.8 and 25.3 kg P/ha, respectively). However, site-year had a larger impact on net P removal, and the P value for the interaction of site-year with hybrid was 0.009 (Table 3). Similar to fruit size (Table 4), net P removal by 'Galahad' was more substantially impacted by site-year than the other hybrids (Fig. 4). The greatest net P removal was from CCF 2021 (30.1 kg P/ha), and the least was from SROC 2022 (18.3 kg P/ha). This was reasonable because net P removal was strongly correlated with the total yield ($r = 0.821$; $P < 0.001$) (Fig. 3, Supplemental Fig. 3), and the total yield from CCF 2021 was greatest (Fig. 1). Net P removal was calculated from the yield and P concentration, and the P

concentration from fruits harvested at CCF in 2021 was also greatest; the correlation between the P concentration and net P removal reflects that as well (Fig. 3). The positive correlation was consistent in the two grafting treatments (Fig. 3) and three hybrids (Supplemental Fig. 3). These data suggest that under conditions similar to ours, increases in the yield or P concentration would independently lead to increases in net P removal if there was no negative relationship between yield and P concentration.

Grafting increased P removal by 28% (95% CI: 16–40) (Fig. 5). This is a clear and substantial increase. Vargha and Delaney's A of 0.84 supports this assertion (95% CI: 0.69–0.93). It is clear from these results that grafted plants removed more soil P than nongrafted plants under the high soil P conditions of the three site-years used in this study. In a study of tomato and eggplant grafted onto tomato rootstock, tomato P removal was 47% greater in grafted plants compared with nongrafted plants, mainly because of an increase in yield. However, 141% greater P removal was possible in grafted eggplant because of a higher P concentration despite lower yield (Leonardi and Giuffrida 2006).

This study did not include direct postharvest measurements of soil P, and it can be difficult to make assumptions about P soil test results based on P removal. The time lag for soil P drawdown can be extensive (Sharpley et al. 2013), but soils high in P can show a greater rate of P drawdown than soil low in P (Schulte et al. 2010; Verloop et al. 2010). Modeling P drawdown in a forage system

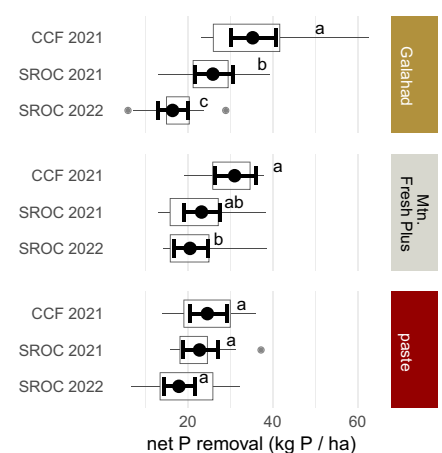


Fig. 4. Net phosphorus (P) removed by tomato harvest in three site-years (CCF 2021, SROC 2021, and SROC 2022) within three tomato hybrids ($n = 15$ per site-year within hybrid). Boxplots illustrate raw data. The box width is the interquartile range (IQR; first to third quartiles), and whiskers extend from the box to the largest value no further from the IQR than 1.5-times the IQR. Outliers (included in the analysis of variance) are shown beyond whiskers. Marginal means are shown as circles within the IQR. Error bars represent the 95% confidence interval (CI) of the marginal mean. Lowercase letters indicate differences based on Tukey's honest significant difference (HSD) within the hybrid ($\alpha = 0.05$).

found that drawdown estimates were highly variable, but that lowering soil P from "excess" to "target" levels in that study would require an average of 7 to 15 years in a nonlinear fashion (Schulte et al. 2010). Additionally, within-field variability of legacy P loss and drawdown potential can be very high, partly because of within-field yield potential differences (Mattila 2023).

One study involving a corn-soybean rotation measured the time to drawdown high levels of soil P to a level at which a response to P fertility was apparent (Dodd and Mallarino 2005); it included soils similar to the current study and found that at least 10 years without P was required to notice a response to P fertilizer (Dodd and Mallarino 2005). Our measured P removal (21.0 for nongrafted tomatoes and 26.9 for grafted tomatoes) was similar to the P removal measured for soybean in our region (Gaspar et al. 2017). However, P removal in the current study was approximately five-times less than that of field corn in a recent experiment (Galindo et al. 2021), suggesting drawdown from tomato fruit harvest likely would be slower than it was in the corn-soybean rotations cited. The number of years it would take to drawdown soil P from "very high" test levels in a tomato monoculture is speculative at this point, but it may be approximately 28% faster when using grafted tomatoes based on the measured 28% increase in P removal compared with that of nongrafted plants.

For vegetable growers and gardeners, emphasizing 4R (right source, right rate, right time, and right place) nutrient management

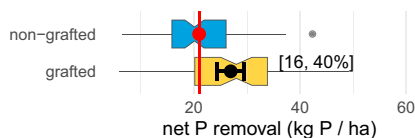


Fig. 5. Net phosphorus (P) removal by tomato harvest from nongrafted tomatoes ($n = 81$) or tomatoes grafted onto 'Estamino' rootstock ($n = 54$). Data include three scion hybrids and three site-years. Boxplots illustrate raw data. The box width is the interquartile range (IQR; first to third quartiles), and whiskers extend from the box to the largest value no further from the IQR than 1.5-times the IQR. Outliers (included in the analysis of variance) are shown beyond whiskers. Notches in boxplots illustrate a model-independent confidence interval (CI) of the median ($1.58 \times \text{IQR}/\sqrt{n}$). The red line indicates the marginal mean of the nongrafted treatment, and the error bar is the 95% CI of the contrast between grafted and nongrafted. The relative response to grafting (% of nongrafted, 95% CI) is shown in brackets.

for P, and especially emphasizing soil testing and applying composts, manure, and mineral P to only meet crop P requirements, should be priorities to minimize P accumulation or P loss from soil (King et al. 2018; Kleinman et al. 2022; Small et al. 2019a). Under high soil P conditions in our study, the starter fertilizers used were ineffective at increasing net P removal and provided no economic benefit, and they also did not measurably increase soil P accumulation and were likely superfluous. Cultural practices, such as using grafted tomatoes, may help to drawdown soil P more quickly, reducing the potential for an environmental impact. However, site-specific and cultivar-specific interactions are likely important considerations for growers to understand (Shonerd et al. 2023).

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