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How to Help Your Plants Hold Their "P" in Container-Based Nursery Production

Jacob H. Shreckhise[1] and James E. Altland[2]

[1]U.S. Department of Agriculture, Agricultural Research Service, U.S. National Arboretum, Floral and Nursery Plants Research Unit, Otis L. Floyd Nursery Research Center, 472 Cadillac Lane, McMinnville, TN 37110, USA. [2]U.S. Department of Agriculture, Agricultural Research Service, Application Technology Research Unit, 1680 Madison Ave., Wooster, Ohio 44691, USA

jacob.shreckhise@usda.gov

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Summary

Pine bark substrate used for container-based nursery crop production poorly retains phosphorus (P), resulting in much of the applied P leaching from containers. Research was conducted to evaluate the effect of $FeSO_4 \cdot 7H_2O$ (ferrous sulfate heptahydrate)-amended pine bark in nursery containers, added as a bottom layer (50% volume) or sole substrate, on P leaching and plant growth of economically important nursery crops. Freeman maple (*Acer* ×*freemanii* 'Jeffersred' Autumn Blaze®), panicle hydrangea (*Hydrangea paniculata* 'SMNHPRZEP' Zinfin Doll®), shrub rose (*Rosa* ×'HORCOGJIL' At Last®), nandina (*Nandina domestica*), and arborvitae (*Thuja* ×'Green Giant') were grown for 13 weeks in 6.1-L (#2) containers with surface-applied controlled-release fertilizer [(CRF); 16N−2.6P−9.1K + micronutrients] and received daily overhead irrigation that was periodically adjusted to achieve a 0.35 leaching fraction. Plants were grown in one of four substrate treatments comprised of dolomite-amended pine bark with: 1) no $FeSO_4 \cdot 7H_2O$ (control); 2) 1.5 kg/m^3 (2.5 lbs/yd^3) $FeSO_4 \cdot 7H_2O$ (FS-1.5); 3) 3 kg/m^3

(5 lbs/yd^3) $FeSO_4 \cdot 7H_2O$ (FS-3); or 4) stratified substrate (FS-3St) in which containers had a 2.5-L layer of FS-3 in the bottom and a 2.5-L layer of the control substrate on top. All leachate from Freeman maple was collected from each container weekly and analyzed for P. Relative to the control, the FS-1.5, FS-3, and FS-3St treatments reduced P leaching by 32%, 57%, and 54%, respectively. Shoot and root dry weight of panicle hydrangea, nandina, shrub rose, and arborvitae were unaffected by substrate treatments. Freeman maple had highest dry weight when grown in the control, but there were no differences in visual quality among treatments. Pine bark amended with 3 kg/m^3 $FeSO_4 \cdot 7H_2O$ either layered in the bottoms of nursery containers or used as the sole substrate can substantially reduce P leaching without affecting growth of four economically important shrub taxa; however, additional fast-growing taxa with high nutrient requirements (like Freeman maple) should be evaluated.

INTRODUCTION

Approximately 80% of U.S. nursery operations produce crops in above-ground containers (USDA, 2019). Substrates commonly used for container-based production, predominantly pine bark in the eastern U.S., are inherently low in plant-essential nutrients and have poor nutrient-holding capacities (Majsztrik et al., 2011). Frequent replenishment of the substrate with nutrients, whether by liquid feeding or applying a controlled-release fertilizer (CRF), is therefore essential to producing a salable crop. However, the constant presence of a soluble or solubilizing fertilizer in a substrate that poorly retains nutrients, paired with frequent (often daily) irrigation and periodic rainfall, results in excess nutrients leaching from containers. Phosphorus (P) is particularly prone to leaching from pine bark-based substrates (Cole and Dole, 1997; Godoy and Cole, 2000; Yeager and Barrett, 1984, 1985a, 1985b). For example, Yeager and Barrett (1984) showed that when 3 kg/m^3 superphosphate was incorporated into a substrate composed of 2 pine bark: 1 peatmoss: 1 sand, 76% of the applied P leached from the substrate in just three weeks of once-daily irrigation.

Nutrients that drain from nursery containers can subsequently runoff to surface waters. Phosphorus contamination of surface waters has been linked to eutrophication and harmful algal blooms that are responsible for annual “dead zones” that plague the Gulf of Mexico, Chesapeake Bay, Lake Erie, Florida Everglades, Lake Okeechobee, and other economically and ecologically important water bodies (Wurtsbaugh et al., 2019). The impact of agricultural P runoff on surface water quality has resulted in increased environmental regulation, a trend that will likely continue in an effort to remediate and preserve impaired waterways. The nursery industry is not immune to state-mandated nutrient management laws. For example, Maryland’s Water Quality Improvement Act of 1998 requires all agricultural operations (including ornamental plant nurseries) grossing ≥$2,500 to submit nitrogen (N) and P management plans and file annual reports on N and P applications (Majsztrik and Lea-Cox, 2013). More recently, Florida enacted Senate Bill 712 (the "Clean Waterways Act") in 2020 which requires all agricultural landowners and growers to submit N and P application records to the Florida Department of Agriculture and Consumer Services; individuals who fail to do so may be reported to the Florida Department of Environmental Protection for "regulatory action."

Best Management Practices (BMPs), i.e., voluntary activities, prohibitions, and cultural practices designed and implemented to preserve and/or remediate water resources, have been widely adopted by containerized nurseries in the U.S. (Bilderback et al., 2013). Fertilizing with a CRF instead of soluble forms is among the most widely implemented BMPs for fertilizer management according to survey studies in Virginia and Alabama (Fain et al., 2000; Mack et al., 2017). However, P leaching from CRF-fertilized containerized crops can be substantial. Broschat (1995), Million et al. (2007a, 2007b), Tyler et al. (1996a, 1996b), and Million and Yeager (2021) reported that 7% to 47% of P applied in controlled-release fertilizer was found in the leachate of containerized crops grown in pine bark-based substrates. Closely monitoring and managing irrigation to avoid excessive leaching (e.g., maintaining a leaching fraction of <0.15) can reduce P leaching (Owen et al., 2008; Tyler et al., 1996b). However, precisely managing irrigation to minimize water and nutrient leaching from container-grown crops is challenging for even the most experienced growers. Furthermore, when using micro-irrigation for outdoor containerized nursery production, rainfall may void the nutrient retention benefits of managing irrigation to maintain a low leaching fraction (Million and Yeager, 2021).

Modifying the charge properties of conventional substrate components (e.g., pine bark) through a process called cationization is a novel but simple approach to reducing P leaching losses from containerized crops, even during heavy rainfall events or when irrigation is overapplied. Cationization can be accomplished by amending an organic material with a metal salt. As the metal salt dissolves, the metal cations rapidly adsorb to the surface of the organic material resulting in an increase in anion binding sites. Metal-loaded agricultural by-products (e.g., sugarcane bagasse, coir pith, wood particles, okara) have been studied extensively for their capacity to sequester phosphate (PO_4^{3-}) from wastewater (Nguyen et al., 2014; Pokhrel et al., 2019). Relative to other metal compounds that have been used to cationize organic materials [e.g., $ZnCl_2$, ZrO_2Cl, $La(NO_3)_3$], iron salts are less expensive, non-toxic, and more readily available for purchase (Pokhrel et al., 2019). Ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$) is one such soluble iron compound that is often used in containerized nursery production as a pre-plant Fe fertilizer (usually a component of a complete micronutrient fertilizer). When mixed into pine bark substrate along with superphosphate, $FeSO_4 \cdot 7H_2O$ has been shown to reduce the amount of water-extractable P from the substrate (Handreck, 1992). However, the effects of amending substrate with relatively high rates of $FeSO_4 \cdot 7H_2O$ (i.e., 1.5 to 3 kg/m^3) on P leaching and growth of containerized nursery crops has not yet been investigated.

Depending on the nature of the bark-Fe-P complexes, the adsorbed P may or may not be available for plant uptake. Adding a layer of $FeSO_4 \cdot 7H_2O$-amended pine bark to the bottoms of the plant containers with the remainder of the container filled with a standard pine bark substrate may be a way to avoid possible reductions in P availability to plants while still mitigating P leaching from the container. In this stratified substrate system, P that is released from the fertilizer and leaches past the root zone would be adsorbed to the $FeSO_4{\cdot}7H_2O$-amended bark before draining from the container. Growing nursery and greenhouse crops in containers with strategic layers of substrate has recently been proposed as a means to decrease fertilizer requirements (Fields et al., 2021), reduce weed growth and weed seed germination (Khamare et al., 2022a and 2022b), and mitigate crop water stress during drought (Criscione et al., 2022). However, stratifying substrate to reduce nutrient leaching from containers has not yet been investigated. The objectives of this research were to investigate the effect of a $FeSO_4{\cdot}7H_2O$-amended pine bark as a bottom layer or throughout container on P leaching and plant growth of five economically important nursery crops.

MATERIALS AND METHODS

Three pine bark batches containing varying rates of agricultural-grade $FeSO_4{\cdot}7H_2O$ and pulverized dolomite were produced using a ribbon mixer [Twister I (single phase); Bouldin & Lawson, McMinnville, TN] with a 5-minute mixing time after all amendments had been added. Batch 1 contained 0.79 kg/m^3 (1.34 lbs/yd^3) pulverized dolomite and no $FeSO_4{\cdot}7H_2O$; Batch 2 contained 2.37 kg/m^3 (3.99 lbs/yd^3) pulverized dolomite and 1.5 kg/m^3 (2.5 lbs/yd^3) $FeSO4{\cdot}7H_2O$; and Batch 3 contained 3.27 kg/m^3 (5.51 lbs/yd^3) pulverized dolomite and 3 kg/m^3 (5 lb/yd^3) $FeSO_4{\cdot}7H_2O$. The dolomite rate varied between batches to achieve a starting pH of ~5.5 in all batches while compensating for the acidifying effect of the $FeSO_4{\cdot}7H_2O$ as it dissolves and hydrolyzes. Black plastic, 6.1-L (#2) containers were each filled to 5 L with the substrate batches according to the treatments shown in **Fig. 1**.

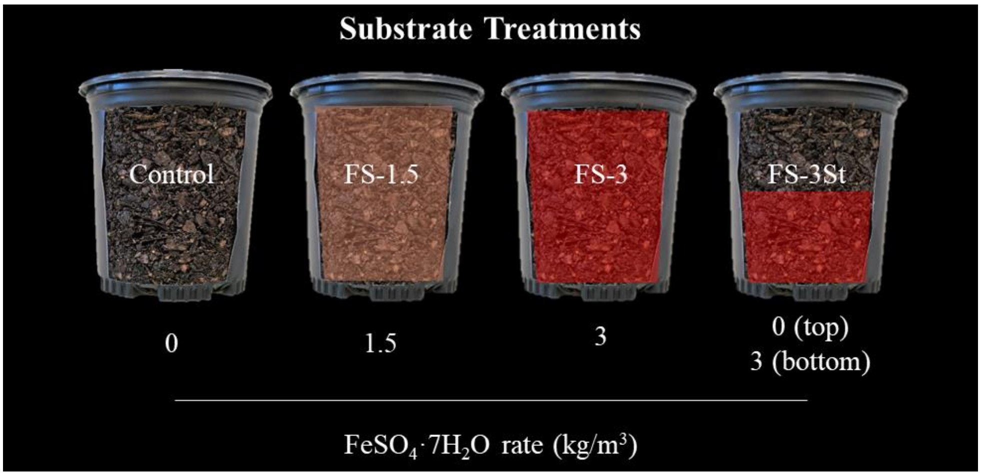

Figure 1. Illustration of substrate treatments, including the location and rate of $FeSO_4{\cdot}7H_2O$ (ferrous sulfate heptahydrate) incorporated into the pine bark. In addition to $FeSO_4{\cdot}7H_2O$, the control, FS-1.5, and FS-3 substrates were amended with 0.79, 2.4, and 3.3 kg/m^3 pulverized dolomite, respectively.

Containers that represented the control, FS-1.5, and FS-3 treatments contained batches 1, 2, and 3, respectively, throughout the container profile, whereas FS-3St containers were stratified with a 2.5-L layer of Batch 3 in the bottom and a 2.5-L layer of Batch 1 on top.

Ten replicate rooted cuttings per treatment from each of five woody plant taxa (200 plants total) were planted into the substrate-filled containers. Taxa in this experiment included a Freeman maple (*Acer ×freemanii* 'Jeffersred' Autumn Blaze®), panicle hydrangea (*Hydrangea paniculata* 'SMNHPRZEP' Zinfin Doll®), shrub rose (*Rosa* ×'HORCOGJIL' At Last®), nandina (*Nandina domestica*), and arborvitae (*Thuja* ×'Green Giant'). All newly potted plants were top-dressed with 33.8 g (medium rate) of a 5- to 6-month CRF [16N−2.6P−9.1K + micronutrients (16N−6P_2O_5−11K_2O); Harrell's, Lakeland, FL].

On 15 June 2021, plants were placed on an open-air gravel pad separated according to taxa, and plants within each taxon were completely randomized. Due to differences in water requirements, Freeman maple, panicle hydrangea, and shrub rose were placed in an irrigation zone separate from arborvitae and nandina. All plants were irrigated daily at 5:00 via overhead sprinklers (High-angle Xcel-Wobbler, #7 nozzle, Senninger Irrigation, Clermont, FL). Leaching fraction (water volume leached ÷ water volume applied) was measured on five randomly selected plants per taxa every two weeks, and irrigation duration was adjusted to maintain a leaching fraction of 0.35. While this target leaching fraction (0.35) is higher than BMPs recommendation of 0.1 to 0.15 (Bilderback et al., 2013) – a leaching fraction of 0.35 more closely mimics commercial nursery settings (personal observation).

Leachate from each Freeman maple was collected continuously for 13 weeks. To collect the leachate resulting from all irrigation and rainfall, Freeman maples were nested in black, 18.9-L (5-gallon) buckets with 30-cm-deep basket lids (HG10MESHPOT; Hydrofarm, Philadelphia, PA) such that the bottom of the plant container was suspended ~6.5 cm above the bottom of the bucket (**Fig. 2**).

Figure 2. Illustration of the leachate collection system.

Plastic capes were taped around the plant containers at ~2 cm below the container lip and draped over the bucket to prevent evaporation of the leachate, minimize sunlight reaching the leachate, and deflect rain and irrigation water from running directly into the leachate buckets. The capes were 63 cm × 63 cm squares of 6 mil black plastic sheeting (Poly-America, Grand Prairie, TX). Reflective bubble insulation (BP48025, Reflectix, Markleville, IN) was wrapped around each leachate bucket to prevent high leachate temperatures. Every 7 days, leachate was weighed to approximate volume (1 g ≈ 1 mL), sampled for later P analysis, and the remaining leachate was discarded. Leachate samples were stored at -20 °C until the end of the study and then thawed, digested to solubilize any particulate P, and analyzed for total P.

At 13 weeks after potting, all plants were measured to calculate growth index [(height + widest width + perpendicular width) ÷ 3], and foliar samples were harvested according to species-specific protocols described by Bryson et al. (2014). Foliar samples were oven-dried at 65 °C, ground to a <0.5 mm particle size using a Cyclone Sample Mill (model 3010-030; UDY, Fort Collins, CO), and sent to a commercial laboratory to be analyzed for P concentration. Plant shoots were severed level with the substrate and roots were separated from the substrate via compressed air. Shoots and roots were oven-dried at 65 °C and separately weighed to obtain shoot dry weight (SDW) and root dry weight (RDW).

Data were subjected to analysis of variance (ANOVA), and post-hoc means separation was accomplished using Tukey's Honestly Significant Difference test (α = 0.05). Statistical analyses were performed using JMP Pro 17 software.

RESULTS AND DISCUSSION

P leaching. During the first four weeks after potting, leachate P from Freeman maples potted in FS-1.5, FS-3, or FS-3St was 71% to 94% lower than that from Freeman maples planted in the control substrate (**Fig. 3**).

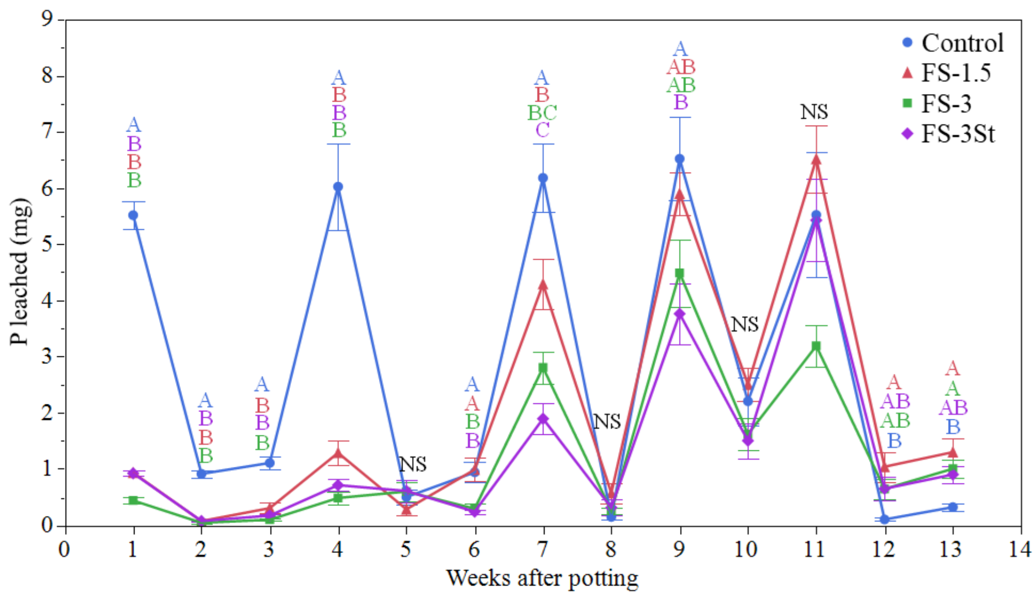

Figure 3. Phosphorus (P) content (± SE) in 7-day cumulative leachate collected once weekly for 13 weeks from containerized (#2) Freeman maples (*Acer ×freemanii* 'Jeffersred' Autumn Blaze) grown in in dolomite-amended pine bark with 1) no $FeSO_4{\cdot}7H_2O$ (control), 2) 1.5 kg/m^3 $FeSO_4{\cdot}7H_2O$ (FS-1.5), 3) 3 kg/m^3 $FeSO_4{\cdot}7H_2O$ (FS-3), or 4) stratified substrate (FS-3St) in which containers had a 2.5-L layer of FS-3 in the bottom and a 2.5-L layer of the control on top. Different letters stacked at a given week (colored to match the treatment they represent) indicate means are significantly different according to Tukey's Honestly Significant Difference Test (α = 0.05). NS = not significantly different.

Thereafter, the FS-1.5 treatment did not significantly reduce P leaching relative to the control, whereas FS-3 and FS-3St were generally effective through weeks 7 and 9, respectively. Diminishing efficacy of the $FeSO_4 \cdot 7H_2O$ treatments over time suggests the adsorption sites for P were becoming saturated. Interestingly, at weeks 12 and 13, the non-stratified $FeSO_4 \cdot 7H_2O$ treatments tended to leach more P than the control. This may have been a result of higher root and shoot biomass (**Table 1**) and thus greater P uptake of the Freeman maples growing in the control substrate relative to those in the FS-1.5 and FS-3 treatments. Resolubilization of P from bark-Fe-P complexes is another possible explanation for more P leaching from FS-1.5 and FS-3 versus the control at weeks 12 and 13. However, evidence of delayed P release from bark-Fe complexes has not been observed in previous, longer-term (19-week) experiments during which leachate was collected from fallow containers with substrate treatments similar to those in the current study (unpublished data).

Freeman maples potted in the control substrate leached a total of 37 mg P over the course of the experiment (**Fig. 4**). By contrast, Freeman maples in the FS-1.5 substrate leached 25.2 mg P (32% reduction) and those in the FS-3 and FS-3St substrates leached between 16 and 17 mg P (57% to 54% reduction, respectively). Similar P retention by the FS-3 and FS-3St treatments, despite the FS-3 containers having twice the amount of $FeSO_4 \cdot 7H_2O$, suggests that $FeSO_4 \cdot 7H_2O$-amended pine bark in the upper half of the container had a nominal effect on P retention. This is further supported by our finding that less P leached from FS-3St compared to FS-1.5 even though these two treatments had the same amount of $FeSO_4 \cdot 7H_2O$ per container. Poor P adsorption by Fe-charged pine bark in the upper portion of the container may be related to its lower moisture content relative to substrate near the bottom of the container.

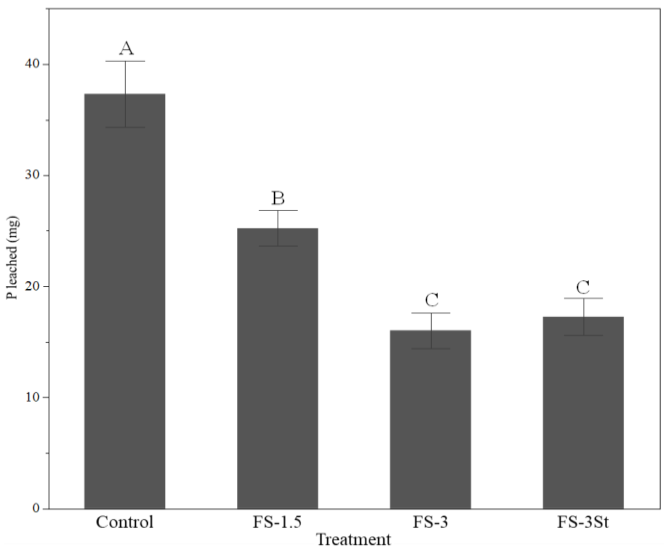

Figure 4. Cumulative phosphorus (P) leached (± SE), on average, from containerized (#2) Freeman maple (*Acer ×freemanii* 'Jeffersred' Autumn Blaze) grown for 13 weeks in dolomite-amended pine bark with 1) no $FeSO_4 \cdot 7H_2O$ (control), 2) 1.5 kg/m^3 $FeSO_4 \cdot 7H_2O$ (FS-1.5), 3) 3 kg/m^3 $FeSO_4 \cdot 7H_2O$ (FS-3), or 4) stratified substrate (FS-3St) in which containers had a 2.5-L layer of FS-3 in the bottom and a 2.5-L layer of the control on top. Different letters above bars indicate mean values are significantly different according to Tukey's Honest Significant Difference Test (α = 0.05).

Table 1. Growth index [(height + widest width + perpendicular width) ÷ 3], shoot dry weight (SDW), root dry weight (RDW), and foliar phosphorus (P) concentrations of containerized Freeman maple (*Acer ×freemanii* 'Jeffersred' Autumn Blaze®), panicle hydrangea (*Hydrangea paniculata* 'SMNHPRZEP' Zinfin Doll®), shrub rose (*Rosa* ×'HORCOGJIL' At Last®), nandina (*Nandina domestica*), and arborvitae (*Thuja* ×'Green Giant') after being grown for 13 weeks in dolomite-amended pine bark with 1) no $FeSO_4 \cdot 7H_2O$ (control), 2) 1.5 kg/m^3 $FeSO_4 \cdot 7H_2O$ (FS-1.5), 3) 3 kg/m^3 $FeSO_4 \cdot 7H_2O$ (FS-3), or 4) stratified substrate (FS-3St) in which containers had a 2.5-L layer of FS-3 in the bottom and a 2.5-L layer of the control on top.

Taxa	Treatment	Growth index (cm)	SDW (g)	RDW (g)	Foliar P (%)
Freeman maple	Control	53.1 a[z]	64.8 a	48.3 a	0.22 a
	FS-1.5	42.6 b	50.9 b	41.8 ab	0.21 ab
	FS-3	43.0 b	50.6 b	40.1 b	0.19 b
	FS-3St	47.0 ab	53.6 b	37.7 b	0.20 b
	P-value	0.0051	0.0001	0.0079	0.0013
panicle hydrangea	Control	31.9	35.1	10.20	0.24
	FS-1.5	31.3	28.7	7.01	0.23
	FS-3	30.8	31.6	8.33	0.19
	FS-3St	32.2	34.2	8.49	0.24
	P-value	0.9010	0.2400	0.1542	0.0563
nandina	Control	45.9	31.6	7.21	0.19
	FS-1.5	43.0	29.4	6.85	0.19
	FS-3	44.1	33.0	7.02	0.18
	FS-3St	43.0	25.4	6.25	0.18
	P-value	0.4690	0.4380	0.7809	0.7666
shrub rose	Control	30.7	28.0	13.8	0.20 a
	FS-1.5	29.8	26.9	13.6	0.17 ab
	FS-3	28.7	27.0	14.0	0.16 b
	FS-3St	27.9	22.4	13.9	0.19 a
	P-value	0.2730	0.1928	0.8542	0.0038
arborvitae	Control	33.1	18.1	3.28	0.26
	FS-1.5	32.3	19.8	3.15	0.25
	FS-3	32.8	23.7	3.93	0.24
	FS-3St	31.4	17.7	3.32	0.27
	P-value	0.5460	0.0998	0.1216	0.1084

[z]Mean values with different letters within the same column and taxon are significantly different according to Tukey's Honestly Significant Difference test ($P < 0.05$).

Rainfall effect on P leaching. The P leaching pattern over time was strongly influenced by rainfall. Weeks during which plants received >3 cm of rainfall (weeks 1, 4, 7, 9, 10, and 11**; Fig. 5**) corresponded with spikes in P leaching (**Fig. 3**). These "rainy weeks", which represented less than half the total number of samplings, accounted for 89% of the cumulative P leached from the control plants over the 13-week period. Greatest reductions in P leaching by the $FeSO_4 \cdot 7H_2O$ treatments relative to the control also occurred during rainy weeks. For example, on weeks 1, 4, and 7 (weeks with 3.5 to 6 cm rainfall), Freeman maples in FS-3 leached, respectively, 5.1, 5.5, and 3.4 mg less P than the control; during weeks 2, 3, 5, and 6 (weeks with 0.2 to 1.3 cm rainfall), the FS-3 treatment reduced P leaching, relative to the control, by 0.1 to 1 mg.

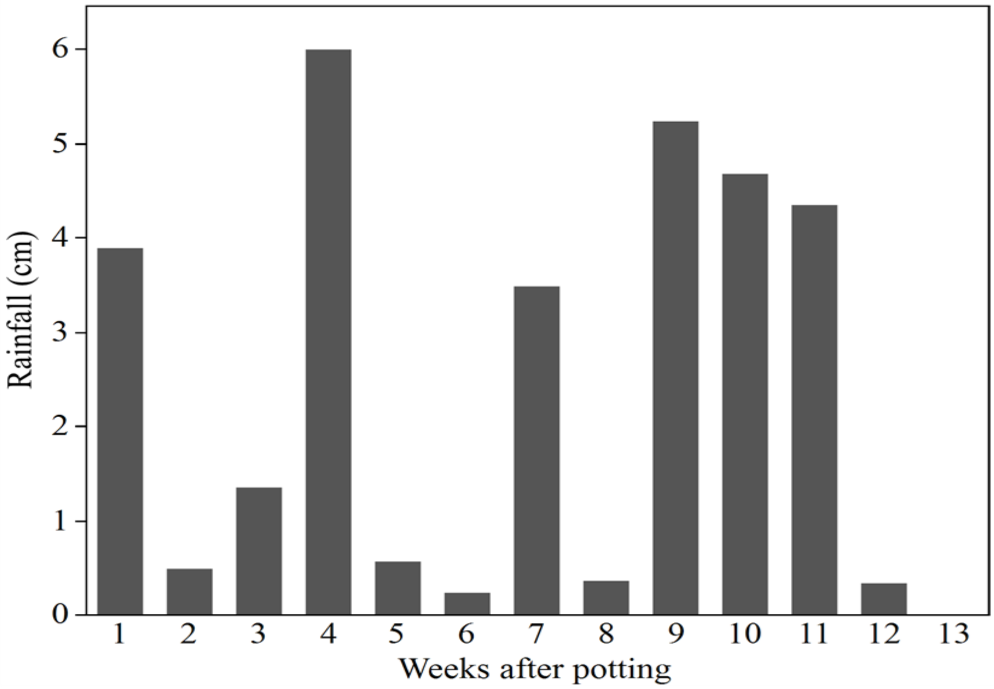

Figure 5. Cumulative rainfall measured once weekly over the course of the 13-week experiment conducted from 15 June 2021 to 14 Sept. 2021 at the Tennessee State Nursery Research Center in McMinnville, TN.

Plant growth, biomass, and foliar P. Growth index, SDW, and RDW of panicle hydrangea, nandina, shrub rose, and arborvitae were unaffected by substrate treatments (**Table 1; Fig. 6**). In contrast, Freeman maples grown in the control substrate had a higher GI than those grown in FS-1.5 or FS-3, higher SDW than those grown in all other treatments, and higher RDW than those grown in FS-3 or FS-3St. Despite these differences in growth among Freeman maples produced in the various substrate treatments, differences in visual quality were not apparent (**Fig. 7**).

One possible explanation for reduced growth and biomass of Freeman maples in the FS treatments is that they were mildly deficient in P. Foliar P concentrations of Freeman maples grown in the control were equal to the lower limit of the survey range (0.22% to 0.29% P) for healthy 'Jeffersred' (Autumn Blaze) Freeman maples (Bryson and Mills, 2014), and Freeman maples grown in FS-3 or FS-3St had lower foliar P concentrations than those in the control. If the survey range is representative of the true sufficiency range, even a slight reduction in P availability to plants that are already near the critical deficiency concentration could result in growth limitation.

Figure 6. Panicle hydrangea (*Hydrangea paniculata* 'SMNHPRZEP' Zinfin Doll®), nandina (*Nandina domestica*), shrub rose (*Rosa* ×'HORCOGJIL' At Last®), and arborvitae (*Thuja* ×'Green Giant') after being grown in 6.1-L containers for 13 weeks in dolomite-amended pine bark with 1) no $FeSO_4 \cdot 7H_2O$ (control), 2) 1.5 kg/m^3 $FeSO_4 \cdot 7H_2O$ (FS-1.5), 3) 3 kg/m^3 $FeSO_4 \cdot 7H_2O$ (FS-3), or 4) stratified substrate (FS-3St) in which containers had a 2.5-L layer of FS-3 in the bottom and a 2.5-L layer of the control on top.

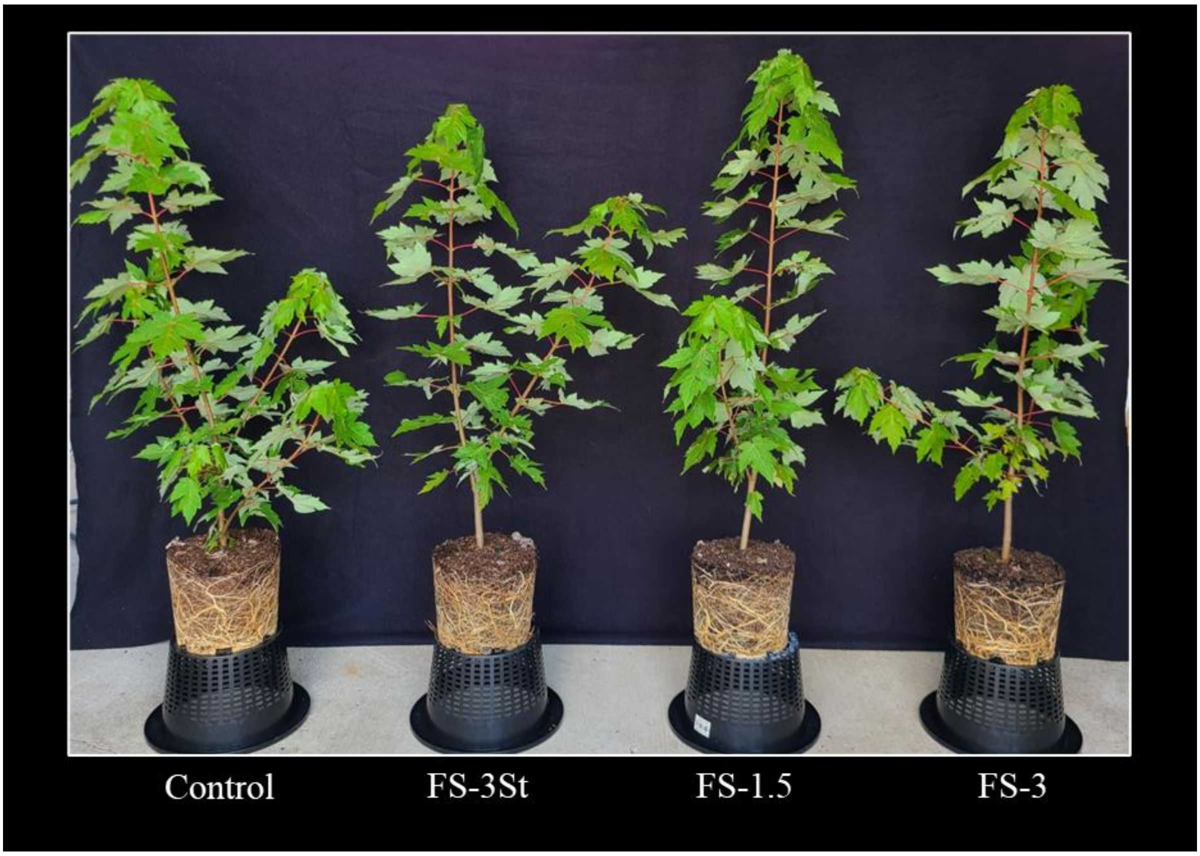

Figure 7. Freeman maple (*Acer ×freemanii* 'Jeffersred' Autumn Blaze) after being grown in 6.1-L containers for 13 weeks in dolomite-amended pine bark with 1) no $FeSO_4{\cdot}7H_2O$ (control), 2) 1.5 kg/m^3 $FeSO_4{\cdot}7H_2O$ (FS-1.5), 3) 3 kg/m^3 $FeSO_4{\cdot}7H_2O$ (FS-3), or 4) stratified substrate (FS-3St) in which containers had a 2.5-L layer of FS-3 in the bottom and a 2.5-L layer of the control on top.

Shrub rose also had lower foliar P concentrations when grown in FS-3 versus the control. However, since lower foliar P concentrations did not correspond with a reduction in plant growth or visual deficiency symptoms, the reduction in foliar P concentration was likely inconsequential to the plant. These corroborated results reported by Johansson (1978) who reported that *Rosa* 'Parel van Aalsmeer' showed no signs of P deficiency until foliar P concentrations fell to ≤ 0.14%. Panicle hydrangea, nandina, and arborvitae foliar P concentrations were not affected by substrate treatments, suggesting that there was enough soluble P remaining after complexation with bark-Fe that P uptake was unrestricted.

CONCLUSION

Amending pine bark with $FeSO_4{\cdot}7H_2O$ can substantially reduce P leaching from container-grown nursery crops, and the magnitude of this effect increases with increasing $FeSO_4{\cdot}7H_2O$ rate (i.e., from 1.5 kg/m^3 to 3 kg/m^3). Reductions in P leaching provided by the $FeSO_4{\cdot}7H_2O$-amended pine bark were especially important when rainfall was a major contributor to the total leachate volume and excessive leaching was unavoidable. By placing a layer of $FeSO_4{\cdot}7H_2O$-amended pine bark in the lower portion of the container instead of amending the entire substrate volume with $FeSO_4 \cdot 7H_2O$ - the total amount of $FeSO_4 \cdot 7H_2O$ applied can be reduced by half while achieving the same reductions in P leaching. Although the plant availability of P associated with bark-Fe complexes was not measured directly, foliar P analyses indicate that 0.6 kg/m^3 $FeSO_4 \cdot 7H_2O$ may reduce P uptake for some taxa (e.g., Freeman maple and shrub rose) but not others (e.g., arborvitae, panicle hydrangea, and nandina). This reduction in P uptake may not necessarily lead to a reduction in plant growth or quality, as was observed in shrub rose.

Moreover, layering the $FeSO_4 \cdot 7H_2O$-amended bark in the bottom of the container effectively avoided foliar P reductions that were present when the same $FeSO_4 \cdot 7H_2O$ rate was incorporated throughout the substrate. In contrast, reduced biomass and foliar P concentrations of Freeman maples grown in $FeSO_4 \cdot 7H_2O$-amended pine bark (stratified or non-stratified) were likely a consequence of their relatively high nutrient demand (Fulcher et al., 2004), particularly when the plants become rootbound as was observed at harvest.

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