**Dolomite and Micronutrient Fertilizer Affect Phosphorus Fate When Growing Crape Myrtle in Pine Bark**

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**Abstract.** Soilless substrates are routinely amended with dolomite and sulfate-based micronutrients to improve fertility, but the effect of these amendments on phosphorus (P) in substrate pore-water during containerized crop production is poorly understood. The objectives of this research were as follows: compare the effects of dolomite and sulfate-based micronutrient amendments on total P (TP), total dissolved P (TDP), orthophosphate P (OP), and particulate P (PP; TP – TDP) concentrations in pour-through extracts; to model saturated solid phases in substrate pore-water using Visual MINTEQ; and to assess the effects of dolomite and micronutrient amendments on growth and subsequent P uptake efficiency (PUE) of *Lagerstroemia* L. ‘Natchez’ (crape myrtle) potted in pine bark. Containerized crape myrtle were grown in a greenhouse for 93 days in a 100% pine bark substrate containing a polymer-coated 19N–2.6P–10.8K controlled-release fertilizer (CRF) and one of four substrate amendment treatments: no dolomite or micronutrients (control), 2.97 kg·m⁻³ dolomite (FL); 0.89 kg·m⁻³ micro-nutrients (FM); or both dolomite and micronutrients (FLM). Pour-through extracts were collected approximately weekly and fractioned to measure pore-water TP, TDP, and OP and to calculate PP. Particulate P concentrations in pour-through extracts were generally unaffected by amendments. Relative to the control, amending pine bark with FLM reduced water-extractable OP, TDP, and TP concentrations by ~56%, had no effect on P uptake efficiency, and resulted in 34% higher total dry weight (TDW) of crape myrtle. The FM substrate had effects similar to those of FLM on plant TDW and PUE, and FM reduced water-extractable OP, TDP, and TP concentrations by 32% to 36% compared with the control. Crape myrtle grown in FL had 28% lower TDW but pour-through OP, TDP, and TP concentrations were similar to those of the control. Chemical conditions in FLM were favorable for precipitation of manganese hydrogen phosphate (MnHPO₄), which may have contributed to lower water-extractable P concentrations in this treatment. This research suggests that amending pine bark substrate with dolomite and a sulfate-based micronutrient fertilizer should be considered a best management practice for nursery crop production.

Nutrient enrichment and subsequent eutrophication of receiving waters from agriculture have profound effects on aquatic resources. Proliferation of primary producers, including toxic cyanobacteria species, induced by increased nutrient levels in aquatic ecosystems has resulted in loss of species biodiversity, contamination of drinking water, and widespread fish kills (Carpenter et al., 1998). Eutrophication occurs when critical concentrations of both N and P are present; however, P is generally regarded as the limiting nutrient for the accelerated growth of photosynthesizing organisms (e.g., phytoplankton, algae, cyanobacteria, plants) in fresh water ecosystems (Correll, 1998; Khan and Mohammad, 2014; Schindler et al., 2008). Boesch et al. (2001) and Michalak et al. (2015) concluded that P runoff from agricultural operations is a primary contributor to eutrophication in the United States.

Substrates used in containerized nursery crop production predominantly comprise pine bark (*Pinus taeda* L.) in the southeastern United States (Bilderback et al., 2013b; Lu et al., 2006). Pine bark-based substrates have little ability to sorb fertilizer P, thus enabling P to readily leach from containers during irrigation (Marconi and Nelson, 1984; Paradelo et al., 2017; Yeager and Wright, 1982). The best management practice (Bilderback et al., 2013a) of using polymer- or resin-coated controlled-release fertilizers (CRFs) is, in part, used to reduce P leaching and runoff relative to the use of soluble fertilizers (Broschat, 1995; Diara et al., 2014). According to survey studies, CRFs have been widely adopted by the nursery industry in the United States (Dennis et al., 2010; Fain et al., 2000; Mack et al., 2017). However, P uptake efficiency (PUE; percent of applied P taken by plant roots) is generally poor for container-grown nursery crops fertilized with CRFs and ranges from 7% to 62%, depending on the fertilization and irrigation management strategies used (McGinnis et al., 2009; Owen et al., 2008; Tyler et al., 1996b; Warren et al., 1995, 2001).

The PUE in containerized crop production is affected by cultural practices and substrate amendments. Studies by Lea-Cox and Ristvey (2003) and Ristvey et al. (2004, 2007) found that decreasing the P fertilization amount increased the PUE of *Rhododendron* L. ‘Karen’. Warren et al. (1995) determined that resin-coated P resulted in higher PUE than sulfur-coated P or composted turkey litter when producing *Rhododendron* L. ‘Sunglow’. McGinnis et al. (2009) observed higher PUE of *Hibiscus moscheutos* L. ‘Luna Blush’ when supplying P via vermicompost compared with CRF. When growing containerized *Cotoneaster dammeri* C.K.Schneid. ‘Skogholm’, Owen et al. (2008) reported improved PUE in plants that received a 50% lower CRF-P application rate or when grown in pine bark substrate amended with 11% (by volume) calcined palygorskite clay. Other studies have demonstrated that various clay products reduce P leaching from containers when mixed into a pine bark substrate (Ogutu and Williams, 2009; Owen et al., 2007; Ruter, 2004).

Dolomite [CaMg(CO₃)₂] and micronutrient amendments are routinely mixed into container substrates before potting. Dolomitic limestone is used to increase substrate pH and supply plants with calcium (Ca) and...
magnesium (Mg). Phosphorus sorption by dolomite has been well-established in studies examining its use as a P adsorbent for wastewater treatment (Karaca et al., 2004, 2006; Mangwandi et al., 2014; Xu et al., 2014; Yuan et al., 2014, 2015). Additionally, the ability of dolomite to sorb P in peat-or pine bark-based substrates has been studied during containerized crop production research (Argo and Biernbaum, 1996a, 1996b; Havis and Baker, 1985; Haynes, 1982; Shreckhise et al., 2019).

Micronutrient fertilizers provide boron (B), chloride (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn) in sulfated or chelated forms, and some micronutrient fertilizers supply plants with additional Ca and Mg. Shreckhise et al. (2019) found that compared with a nonamended substrate, a sulfate-based micronutrient fertilizer reduced orthophosphate P (OP) concentrations in leachate by more than 50% in fallow columns of CRF-phosphate P (OP) concentrations in leachate by more than 50% in fallow columns of CRF-phosphate P. Therefore, effluent P associated with metals supplied by the dissolution of dolomite and micronutrients (e.g., Ca, Mg, Mn, Fe), would not have been detected and may account for a portion of the nonrecovered P. When measuring P fractions in leachate of daily irrigated (i.e., 0.26 cm–1) fallow pine bar columns, Shreckhise et al. (2019) reported that OP contributed between 12% and 50% of total P (TP) measured on days 1, 5, 9, 15, and 23, regardless of dolomite and micronutrient additions. Comparing relative amounts of TP, total dissolved P (TDP), and OP in pore-water of pine bark substrate containing dolomite and micronutrients would build on our understanding of the fate of P in containerized crop production. The objectives of this research were as follows: 1) compare the effects of dolomite and micronutrient amendments on TP, TDP, OP, and particulate P (PP; TP – TDP) concentrations in pour-through extracts; 2) model saturated solid phases in substrate pore-water with OP during root uptake. How-ever, the effects of dolomite and micronutrients in pine bark substrate on PUE of containerized crops have not been investigated.

Phosphorus recovery has been reported to be between 16% and 57% in containerized nursery trials attempting to recover all fertilizer P partitioned in the effluent, plant, substrate, and nondissolved fertilizer (McGinnis et al., 2009; Owen et al., 2008; Ristvey et al., 2004; Tyler et al., 1996a; Warren et al., 2001). In these studies, a definitive explanation for incomplete P recovery has not been reported. We postulate that low P recovery was a factor of the analytical method used to measure P. The P concentrations in effluent of containerized nursery crops are commonly measured colorimetrically after filtration through a 0.45-μm membrane as dissolved reactive P, which is the P fraction available for plant uptake. In all of the aforementioned P budget studies, effluent P was reported as dissolved reactive P or PO4-P (i.e., orthophosphate P). Therefore, effluent P associated with metals supplied by the dissolution of dolomite and micronutrients (e.g., Ca, Mg, Mn, Fe), would not have been detected and may account for a portion of the nonrecovered P. When measuring P fractions in leachate of daily irrigated (i.e., 0.26 cm–1) fallow pine bar columns, Shreckhise et al. (2019) reported that OP contributed between 12% and 50% of total P (TP) measured on days 1, 5, 9, 15, and 23, regardless of dolomite and micronutrient additions. Comparing relative amounts of TP, total dissolved P (TDP), and OP in pore-water of pine bark substrate containing dolomite and micronutrients would build on our understanding of the fate of P in containerized crop production. The objectives of this research were as follows: 1) compare the effects of dolomite and micronutrient amendments on TP, TDP, OP, and particulate P (PP; TP – TDP) concentrations in pour-through extracts; 2) model saturated solid phases in substrate pore-water using a geochemical speciation software (Visual MINTEQ); and 3) assess the effects of dolomite and micronutrient amendments on growth and subsequent P use efficiency of Lagerstroemia L. ‘Natchez’ (crape myrtle) potted in pine bark with incorporated CRF.

Materials and Methods

On 10 Feb. 2017, 60 dormant Lagerstroemia L. ‘Natchez’ (crape myrtle) liners were acquired in 15-cell trays (1-L cells) from Saunders Brothers Nursery (Piney River, VA). Crape myrtle was chosen due to its popularity in the southeastern nursery industry and relatively fast growth rate, which would ensure a quantifiable level of nutrient uptake. Of the 60 liners, the 20 most uniform single-trunk plants were selected for this study and pruned to a height of 30 cm. Pine bark (aged at least 8 months; 15.9-mm screen) was obtained from Carolina Bark Products (Seaboard, NC) on 21 Feb. 2017. Measured air space and container capacity (by volume) of the substrate were 22.3% and 60.7%, respectively, and bulk density was 0.16 g cm–3 (NCSU porometer method; Fonteno et al., 1995). Pine bark elemental analyses results are reported in Table 1. Additionally, initial pine bark saturated media extracts (n = 3) (Warnke, 1986) contained (in mg L–1 ± se) less than 0.31 NH4-N, less than 0.12 NO3–N, 0.12 ± 0.02 NO2–N, 7.67 ± 0.46 PO4-P (i.e., OP), 25.4 ± 1.51 K, and 9.5 ± 0.90 Cl. Electrical conductivity (EC) and pH values in saturated media extracts were 0.84 ± 0.04 mS cm–1 and 4.9 ± 0.04, respectively. Methods used to determine ion concentrations, EC, and pH have been described by Shreckhise et al. (2019).

On 22 Feb. 2017, pine bark was either nonamended (control) or amended with 2.97 kg m–3 dolomite (FL), 0.89 kg m–3 micronutrients (FM), or both dolomite and micronutrients (FLM). The dolomite was supplied as 50% pulverized dolomite [94% CaCO3 equivalent (CCE); Old Castle Lawn and Garden, Thomasville, PA] and 50% ground dolomite (97% CCE; Rockydale Quarries Corporation, Roanoke, VA). The pulverized dolomite had 100%, 95%, 72%, and 54% and the ground dolomite had 100%, 90%, 50%, and 35% passing through 2.00-, 0.84-, 0.25-, and 0.15-mm mesh screens, respectively. Collectively, the dolomite mixture contained 21% Ca and 22% Mg (by weight). The granular micronutrient fertilizer (Micromax; ICL Specialty Fertilizers, Dublin, OH) contained 6.00% Ca, 3.00% Mg, 12.00% S, 0.10% B, 1.00% Cu, 17.00% Fe, 2.50% Mn, 0.05% Mo, and 1.00% Zn derived from CaMg(CO3)2, FeSO4·7H2O, MnSO4, ZnSO4, CuSO4·5H2O, Na2B4O7·10H2O, and Na2MoO4·2H2O. Incorporation of dolomite and micronutrients into the substrate was accomplished by mixing for 5 min using a small cement mixer (0.14 m3 capacity; ≈23 rotations per minute). Five 11.4-L aliquots of each of the four substrate mixes were amended with 28 g

Table 1. Pine bark elemental analysis determined by Brookside Laboratories (New Bremen, OH) using a Thermal 6500 Duo inductively coupled plasma optical emission spectrometer (ICP-OES) following microwave-assisted nitric acid digestion (Peters et al., 2005).

<table>
<thead>
<tr>
<th>Element</th>
<th>N (%)</th>
<th>P (%)</th>
<th>K (%)</th>
<th>Ca (%)</th>
<th>Mg (%)</th>
<th>S (%)</th>
<th>B (mg kg–1)</th>
<th>Fe (mg kg–1)</th>
<th>Mn (mg kg–1)</th>
<th>Cu (mg kg–1)</th>
<th>Zn (mg kg–1)</th>
<th>C:N</th>
</tr>
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<td></td>
<td>0.31</td>
<td>0.01</td>
<td>0.10</td>
<td>0.23</td>
<td>0.05</td>
<td>0.04</td>
<td>4.3</td>
<td>1,184.0</td>
<td>79.3</td>
<td>6.9</td>
<td>27.5</td>
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<td></td>
<td>189</td>
</tr>
</tbody>
</table>
from NH\textsubscript{4}NO\textsubscript{3}, NH\textsubscript{4}H\textsubscript{2}PO\textsubscript{4}, and K\textsubscript{2}SO\textsubscript{4}. The
minimize transplant stress. Plants were then
ing substrate was left in the liner root balls to
liner per container. During potting, the exist-
Chambersburg, PA) to plant one crape myrtle
plastic containers (C1200; Nursery Supplies,
then added to 20 respective 11.4-L black
20 substrate aliquots were each hand-mixed
LLC, Lakeland, FL). The CRF was a homo-
water, Victoria, AU), and applied via
irrigation window controllers, each with a
consistently moisture. Watering was followed by
assure uniformity within each container. The ir-
volume was adjusted periodically as
as needed to achieve a target weekly leaching
(volume leached/volume applied) of
The observed average leaching fraction, measured weekly, was 0.20 ± 0.009
over the course of the study. Element con-
concentrations in irrigation water were stable
over time, with the following mean (n = 10)
values (mg·L\textsuperscript{-1} ± se): 13.0 ± 0.38 Ca; 1.3 ±
8.08 K; 5.4 ± 0.17 Mg; 10.3 ± 0.22 Na; 0.1 ±
0.02 Fe; 0.4 ± 0.01 mg·L\textsuperscript{-1} P; 2.0 ± 0.04 S;
0.2 ± 0.02 Zn; and 50.8 ± 2.03 total alkalinity.
Irrigation water pH and EC were 7.1 ± 0.04
mS·cm\textsuperscript{-1} and 0.15 ± 0.002 mS·cm\textsuperscript{-1},
Irrigation preceding pour-through extrac-
tion was accomplished by hand-pouring tap
water through a diffuser to achieve ≥20% leaching.
The diffuser was similar to that described by Shreckhise et al. (2019). This
irrigation method was adopted before pore-
water extraction to further improve moisture
uniformity of the substrate and ensure a
consistent leaching fraction across treatments
and repetitions by individually adjusting irr-
igation volume when necessary. On days 14
and 35, and every 7 d thereafter through 91
DAI, substrate pore-water was extracted
from each plant via the pour-through method
(Wright, 1986). Pour-through extracts were
attained by hand-pouring 300 mL of deion-
ized (DI) water evenly over the substrate
surface 1 h after irrigation and then collecting
the ≈110 mL of subsequent leachate for
analyses. An aliquot of each pore-water sam-
ple was analyzed for pH and EC within 4 h of
pour-through extraction. The remainder of
each sample was divided, prepared, and an-
alyzed for ions, total dissolved (≤0.45 µm
elements, dissolved organic carbon (DOC),
and total (nonfiltered) element concentra-
tions in the same manner as that described by
Shreckhise et al. (2019), except that pore-
water samples collected on a given date were
analyzed individually (i.e., samples were not
combined to form composite samples).
On day 93, plant shoots were severed
level with the substrate surface and triple-
rinsed with both tap and distilled water.
Approximately 80% of the loose substrate
was shaken from roots and set aside for later
collection of CRF granules to determine the
proportion of the initial N, P, and K remain-
ing. A tap water stream was used to
remove the remaining substrate particles adhered to
roots that could not be efficiently removed by
hand. Then, shoots and roots were oven-dried
at 65 °C until the weight remained constant.
Shoot dry weights (SDW) and root dry
weights (RDW) were weighed separately,
su mmed to determine the total dry weight
(TDW), and then ground separately to a 0.5-
mm particle size using a 3379-K35 Variable
Speed Digital ED-5 Wiley Mill (Thomas
Scientific, Swedesboro, NJ) set to 900 rpm.
Ground samples were sent to Brookside Lab-
oratories (New Bremen, OH) for tissue nu-
trient analysis, during which plant samples
were analyzed using a Thermo 6500 Duo
ICP-OES (Thermo Fisher Scientific, Wel-
tham, MA) after microwave-assisted diges-
tion with nitric acid and hydrogen peroxide
(T002 test package). Tissue nutrient concen-
trations were multiplied by the SDW or RDW
values to calculate the P content. The total tissue P content (i.e., the sum of P
amounts in roots and shoots) was calculated
to assess the relative PUE in plants among
substrate treatments.
To determine the amount of N, P, and K
remaining in CRF granules, ≈2 g of oven-
dried CRF from each replication within each
treatment (totaling 20 samples weighing 2 g
each) were collected from the postexperi-
ment substrate. Because the CRF granules
used in this study (Polyon) do not swell and,
therefore, maintain a consistent volume over
time, the postexperiment CRF was compared
with fresh CRF based on volume. The vol-
umes of each of the 20 postexperiment CRF
samples as well as five 2-g samples of fresh
CRF were determined by submerging gran-
ules in 5 mL of DI water contained in a 10-
ml graduated cylinder and measuring
placed water volume (mL). The DI water
and CRF within the graduated cylinder were
then poured into a 1-L volumetric flask and
brought to volume with DI water. The CRF–
DI water mixture was blended for 1 min
using a 12-speed blender (006843-000-NP1;
Oster, Boca Raton, FL) at the highest speed
setting. An aliquot of the blended fertilizer
solution was filtered using a 0.2-µm poly-
vinyldiene fluoride (PVDF) filter diluted 90%
with DI water and then analyzed for NO\textsubscript{3},
NO\textsubscript{2}, NH\textsubscript{4}, PO\textsubscript{4}, and K concentrations
using the ion chromatography system described
by Shreckhise et al. (2019). The amount of each
ion remaining in the CRF was calculated by
dividing the amount (mg) of ions in the
postexperiment CRF by the amount (mg) of ions in fresh CRF based on an equivalent
CRF volume. Compared with the amounts in
fresh CRF, 4%, 0.4%, 1%, and 15% of the
NH\textsubscript{4}, NO\textsubscript{2}, PO\textsubscript{4}, and K, respectively,
remained in the CRF at the end of the experi-
ment, and no differences were observed
among substrate treatments.
Saturation index (SI) values were used to interpret the degree of saturation in solutions with regard to solid phases. Saturation indices were calculated as log(IAP/Ksp), where IAP is the ion activity product and Ksp is the solubility product constant. For a given compound, SI values of <0, 0, or >0 indicate that the solution is undersaturated, saturated, or supersaturated, respectively, with regard to the solid phase.

Statistical analysis. Before analyses, Ca and Mn values were log and Johnson-transformed (Johnson, 1949), respectively, to correct for heteroscedasticity and non-normality. All data collected in pour-through extracts over time were subjected to a two-way repeated measures analysis of variance (ANOVA) with one-between-subjects factor, substrate (control, FL, FM, and FLM), and repeated measures factor, time (14, 35, 42, 48, 56, 63, 70, 77, 84, and 91 DAI). The repeated measures analysis was accomplished via covariance structure modeling (Wolfinger, 1993), in which the most appropriate covariance structure was selected by fitting data to various homogeneous and heterogeneous covariance structures available in JMP Pro 14 (SAS Institute Inc., Cary, NC) and subsequently comparing corrected Akaike information criterion (AICc) values. According to lowest AICc values, the first-order autoregressive (AR[1]) covariance structure was used for all repeated measures analyses. Except when analyzing TDW and P tissue content, the random block effect was removed from the analysis because it did not improve the model fit. When the substrate × time interaction was significant, simple effects were analyzed via Dunnett’s method or Tukey’s honestly significant difference. Substrate effects on dry weight and tissue nutrient content were analyzed using one-way ANOVA, and post-hoc means separation was accomplished using Tukey’s honestly significant difference. Saturation indices for each sampling date and treatment were determined to be significantly greater than 0 (i.e., supersaturated) using a one-sample t test with the hypothesized mean set to “0”. The substrate effect on the linear relationship between TDP (x) and OP (y) or TP (y) was assessed by determining the significance of the substrate × TDP interaction. The correlation between PP and TDP was analyzed using the Pearson correlation coefficient (r). All data were processed using JMP Pro 14 (SAS Institute Inc.), and figures were created using Graph 4.5.3 (Synergy Software, Reading, PA).

Results

Substrate effects on P fractions. The total dissolved P had a strong linear relationship with OP and TP (Fig. 1). In the linear models equating TDP to OP or TP, the substrate × TDP interaction terms were not significant (P = 0.1948 and 0.0650, respectively); therefore, they were removed from both models. When pooled across substrates and time, OP contributed 93% of TDP and TDP contributed 87% of TP (Table 3). In the control, FL, FM, and FLM substrates, TP comprised 79%, 89%, 79%, and 75% OP, respectively, when pooled over time. The main effects of substrate and time and the substrate × time interaction were significant for both OP and TP (Table 2). The main effects of substrate on OP and TDP pooled over time are presented in Table 3. Both OP and TDP concentrations in FL were equivalent to those in the control within the respective fractions, whereas FM and FLM had 55% and 140% lower TDP and 65% and 150% lower OP concentrations, respectively, than FL. Orthophosphate P and TDP concentrations in FM were 32% and 35%, respectively, lower than those in the control, whereas concentrations in FLM were 56% lower than those in the control for these two fractions. Pooled TDP concentrations in FLM were also 36% lower than those in the FM treatment, whereas OP concentrations in FLM were not different from those in FM. Because treatments had similar effects on TDP and OP, and because TDP values were used to calculate PP, simple effects of treatments at each sampling time are reported only for TDP (Fig. 2). From 14 to 42 DAI, pore-water TDP concentrations decreased in the control, FL, and FLM, but they stayed the same in FM. Thereafter, TDP concentrations in all treatments increased until reaching a maximum between 56 and 70 DAI; then, they decreased for the remainder of the study. Total dissolved P concentrations in the FL treatment were higher than or equal to those of the control, except at 14 DAI, during which TDP concentrations were 26% lower in FL than in the control. In the FM substrate, TDP concentrations were 68%, 46%, and 23% lower than those in the control at 14, 35, and 56 DAI, respectively, and were equivalent to those in the control at all other sampling dates. Total dissolved P concentrations in the FLM treatment were between 43% and 73% lower than those of the control at all sampling dates for the first 63 d of the study and at 91 DAI, with greatest differences occurring at 14 to 42 DAI. The main effect of time and the substrate × time interaction were significant for PP; however, the main effect of substrate was not (Table 2). Simple effects of substrates on PP concentrations are illustrated in Fig. 2. Particulate P concentrations were affected by substrate treatments only on the first two sampling days. At 14 DAI, PP concentrations in FM and FLM were 71% and 45%, respectively, lower than those in the control; at 35 DAI, PP concentrations in FM were 72% lower than those of the control. Particulate P concentrations in FL, FM, and FLM were equivalent to those in the control on all sampling dates after 35 DAI. The correlation between PP and TDP was analyzed using

![Fig. 1. Linear relationship between total dissolved phosphorus (TDP) and total phosphorus (TP) concentrations in pour-through extracts of 'Natchez' grown in pine bark with 2.97 kg·m⁻³ dolomite (FL), 0.89 kg·m⁻³ micronutrient fertilizer (FM), and both dolomite and micronutrient fertilizer (FLM). Equations were developed from data pooled across time and substrate treatments (n = 198).](image)
determine if relatively high PP concentrations corresponded with relatively low TP concentrations. Particulate P and TP concentrations had a moderate positive correlation \((r = 0.471; P < 0.0001)\). Similar to TP, PP concentrations in the control and all treatments peaked at 70 DAI before declining for the remainder of the study.

The main effects of substrate and time and the substrate \(\times\) time interaction on TP were significant (Table 2). The main effect of substrate on TP is presented in Table 3. Similar to results described for OP and TDP, pore-water TP concentrations in the control and FL treatment were equivalent, whereas in FM and FLM, TP concentrations were 36% and 56%, respectively, lower than those in the control. Total P concentrations in FLM were also 31% lower than those in FM. Simple effects of substrates on TP at each sampling time are presented in Fig. 2. Total P concentrations in FL were 26% lower than those in the control at 14 DAI and 58% and 103% higher than those in the control at 77 and 91 DAI, respectively. At all other sampling dates, TP concentrations in the control and FL were equivalent. Total P concentrations in the control were the same as those in the control at all sampling dates except 14 and 35 DAI, during which TP concentrations in FM were 69% and 49%, respectively, lower than those in the control. In the FLM treatment, TP concentrations were 40% to 73% lower than those in the control at 14 to 63 DAI.

**Modeling**

Two P species were supersaturated with regard to their solid phases according to SI values calculated by Visual MINTEQ (Table 4). Saturation indices for MnHPO\(_4\) were significantly higher than 0 (i.e., supersaturated with regard to the solid phase) on all sampling dates and in all treatments, including the control. Saturation indices were highest in FLM from 14 to 63 DAI, and in FLM or FL for the remainder of the study. The lowest SI values for MnHPO\(_4\) were generally equivalent to those in FLM. In FM, SI values for MnHPO\(_4\) were greater than 0 and generally higher than SI values in FLM from 42 to 70 DAI. In FLM, SI values for MnHPO\(_4\) were greater than 0 only at 70 DAI. In extracts from the control and FM, the Ca\(_5\)(PO\(_4\))\(_3\)OH solid phase was undersaturated on all sampling dates.

**\(pH\), calcium, and manganese.** Substrate effects on pore-water \(pH\), Ca, and Mn were analyzed to facilitate an interpretation of the predicted occurrence of MnHPO\(_4\) and Ca\(_5\)(PO\(_4\))\(_3\)OH solid phases. Because the substrate and time main effects and the substrate \(\times\) time interaction were significant for \(pH\), Mn, and Ca (Table 2), the simple effects of substrate were examined at each level of time (Fig. 3).

Despite the significant substrate \(\times\) time interaction for \(pH\), pore-water \(pH\) values varied by \(\leq 0.3, 0.6, 0.5,\) and 0.7 units in the control, FL, FM, and FLM, respectively, over the course of the study. When averaged over time, pore-water \(pH\) values of the control, FL, FM, and FLM were 4.3 \(\pm\) 0.2, 6.4 \(\pm\) 0.03, 3.7 \(\pm\) 0.02, and 6.2 \(\pm\) 0.03, respectively.

Pore-water Mn concentrations were highest in FM at all sampling dates, ranging from 18.4 to 1.5 mg L\(^{-1}\) at 14 DAI and 77 DAI, respectively (Fig. 3). Manganese concentrations in FLM were less than one-tenth of those in FM and decreased over the course of the study from 4.1 mg L\(^{-1}\) at 14 DAI to 0.1 mg L\(^{-1}\) at 91 DAI. In the control and FM substrates, Mn concentrations were consistently less than 0.6 and 0.05 mg L\(^{-1}\), respectively, with higher Mn concentrations in the control at all sampling dates.

Calcium concentrations in the control were relatively constant over time, fluctuating between maximum and minimum concentrations of 14 and 6 mg L\(^{-1}\), respectively (Fig. 3). Calcium concentrations in FM were generally equivalent to those in FLM. In FM and FLM, Ca concentrations decreased from 111 or 85 mg L\(^{-1}\), respectively, at 14 DAI to 16 mg L\(^{-1}\) at 77 DAI, and then increased for the remainder of the study. In contrast, Ca concentrations in FL increased from 15 mg L\(^{-1}\) at 14 DAI to a maximum concentration of 32 mg L\(^{-1}\) at 70 DAI, and then decreased to 20 mg L\(^{-1}\) by 91 DAI.

**Plant biomass and tissue phosphorus.** Plants grown in FM or FLM had the highest SDW, RDW, and TDW among the treatments and control (Table 3). Compared with plants grown in FLM, SDW, RDW, and TDW were 29% to 35% lower for plants grown in the control and 51% to 53% lower for plants grown in FL. The SDW and TDW of plants grown in FL were \(\approx 28\%\) lower than those in plants grown in the control, whereas the RDW was the same in these two treatments. The total P content in plant tissue (i.e., shoots and roots) was \(28\%\) higher in plants

### Table 3. Pore-water concentrations of orthophosphate phosphorus (OP), total dissolved phosphorus (TDP), particulate phosphorus (PP), and total phosphorus (TP) pooled over sampling dates (\(n = 200\)) and shoot dry weight (SDW), root dry weight (RDW), final total dry weight (TDW), tissue phosphorus (P) content, and P uptake efficiency (PUE) (\(n = 5\)) of containerized Lagerstroemia ‘Natchez’ grown for 91 d in a pine bark substrate amended with 2.97 kg m\(^{-3}\) of a polymer-coated 19N–2.6P–10.8K controlled-release fertilizer and no additional amendment (control), 2.97 kg m\(^{-3}\) dolomite (FL), 0.89 kg m\(^{-3}\) micronutrient fertilizer (FM), or both dolomite and micronutrient fertilizer (FLM).

<table>
<thead>
<tr>
<th>Substrate</th>
<th>OP (mg L(^{-1}))</th>
<th>TDP (mg L(^{-1}))</th>
<th>PP (mg L(^{-1}))</th>
<th>SDW (g)</th>
<th>RDW (g)</th>
<th>TDW (g)</th>
<th>Tissue P (mg)</th>
<th>PUE%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5.8 a*</td>
<td>6.2 a</td>
<td>0.70</td>
<td>49.9 b</td>
<td>13.1 b</td>
<td>62.9 b</td>
<td>199.2 ab</td>
<td>0.30</td>
</tr>
<tr>
<td>FL</td>
<td>6.1 a</td>
<td>6.4 a</td>
<td>0.85</td>
<td>36.3 c</td>
<td>8.9 b</td>
<td>45.1 c</td>
<td>164.6 b</td>
<td>0.25</td>
</tr>
<tr>
<td>FM</td>
<td>3.7 b</td>
<td>4.2 b</td>
<td>0.53</td>
<td>21.4 a</td>
<td>65.4 a</td>
<td>86.8 a</td>
<td>194.2 ab</td>
<td>0.30</td>
</tr>
<tr>
<td>FLM</td>
<td>2.5 b</td>
<td>2.7 c</td>
<td>0.58</td>
<td>3.3 c</td>
<td>18.3 a</td>
<td>95.3 a</td>
<td>210.8 a</td>
<td>0.33</td>
</tr>
</tbody>
</table>

\*PUE = (mg P in plant tissue) / (mg P released from CRF).

\*Means followed by the same letter within columns are not significantly different according to Tukey’s honestly significant difference (HSD) test.

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**Fig. 2.** Effects of substrate treatments on total dissolved phosphorus (TDP), particulate phosphorus (PP), and total phosphorus (TP) concentrations over time in pour-through extracts of containerized Lagerstroemia ‘Natchez’ grown for 91 d in a pine bark substrate amended with 2.97 kg m\(^{-3}\) of a polymer-coated 19N–2.6P–10.8K controlled-release fertilizer (CRF) and either no amendment (control), 2.97 kg m\(^{-3}\) dolomite (FL), 0.89 kg m\(^{-3}\) micronutrient fertilizer (FM), or both dolomite and micronutrient fertilizer (FLM). Asterisks next to means indicate a significant difference from control within the corresponding sampling date according to Dunnett’s test (\(n = 5\); \(P < 0.05\)). Tukey’s honestly significant difference (HSD) values enable comparisons of concentrations over time within the corresponding treatment. Vertical bars represent the SEM.
the following equation: $\text{TDP} = 0.237 + \text{amended with various rates of FeSO}_4$, citing a mental standpoint because many species of plants grown in FL.

## Discussion

The total dissolved P concentrations (i.e., P concentration in filtered solutions determined via ICP-AES) are routinely measured by analytical laboratories because ICP-AES can conveniently measure all essential plant nutrients, except N, simultaneously. However, because TDP includes dissolved organic P and colloidal P in addition to OP (Van Moorleghem et al., 2011), substrate extract samples are often also analyzed colorimetrically (e.g., molybdate blue method) (Murphy and Riley, 1962) or via ion chromatography to provide a more accurate estimate of plant-available P concentrations. Given that the linear relationship between OP (y) and TDP (x) has a slope of $\approx 1$ and a small y-intercept (~0.359), from a practical standpoint, TDP is a good proxy for OP in pour-through samples, regardless of the presence of dolomite or micronutrient amendments. Hence, analyzing filtered samples via ion chromatography or colorimetry in addition to ICP-AES is unnecessary for interpreting the plant availability of P in pour-through extracts from pine bark substrates. Handreck (1996) came to a similar conclusion when comparing TDP to OP concentrations in 2 mM diethylenetriaminepentaacetic acid (DTPA) extracts of a pine bark substrate amended with various rates of FeSO$_4$, citing the following equation: $\text{TDP} = 0.237 + 1.03(\text{OP})$ ($R^2 = 0.98$).

Total P is often a more informative P fraction than TDP or OP from an environmental standpoint because many species of PP in runoff can become labile for algae consumption in receiving waters (Okubo et al., 2012; Uusitalo et al., 2003). However, analyzing aqueous samples for TP is a laborious process relative to that of TDP or OP, because TP determination often requires a digestion step to solubilize any particulate P in the sample. The strong linear relationship between TDP and TP ($R^2 = 0.98$) and the absence of a TDP $\times$ substrate interaction suggest that TDP is a reliable predictor of TP, regardless of whether sulfate-based micronutrients and dolomite are added to the substrate. Million et al. (2007b) reported a similar relationship between OP and TP in runoff samples from container-grown *Viburnum odoratissimum* (L.) Ker-Gawl: $\text{TP} = 0.03 + 1.10(\text{OP})$ ($R^2 = 0.99$).

Approximately 75% of TP measured in pour-through extracts from FLM was OP. Hence, in studies that could not account for 43% to 84% of applied fertilizer P in the plant, leachate, and substrate (McGinnis et al., 2009; Owen et al., 2008; Ristvey et al., 2004; Tyler et al., 1996a; Warren et al., 2001), a portion of the unrecovered P was likely in the leachate in a form other than OP. This contention is supported by Shreckhise et al. (2019), who reported that, depending on the sampling date, 4% to 69% of TP was OP in leachate of fallow pine bark columns amended with the same dolomite and micronutrient products used in the current study.

Substrate treatment effects on pore-water OP, TDP, and TP have similar interpretations because TDP and TP consisted predominantly of OP and, as a result, the responses of TDP and TP to substrate treatments reflect the response of OP. Our data indicate that amending pine bark with micronutrients can reduce pore-through P concentrations and increase plant biomass without inhibiting the amount of P absorbed by the plants. The overall 35% lower TDP concentrations in FM compared with the control can be attributed to reductions observed at the first two sampling events. Shreckhise et al. (2019) also reported that the effects of micronutrients added to fallow pine bark columns on leachate OP, TDP, and TP were short-term, citing that micronutrients had no effects on these P fractions by the ninth irrigation event. Although the effects of micronutrients on P solubility in pine bark appear to be brief relative to the duration of a growing season, the period during which they most effectively reduce TDP leaching corresponds to the period of greatest leaching losses (Million et al., 2007a). Lower pore-water OP and TDP concentrations in FM compared with the control could not be attributed to precipitation because SI values indicated Ca$_5$(PO$_4$)$_3$(OH) was consistently undersaturated in both substrates and MnHPO$_4$ SI values in the control and FM were generally equivalent. A possible explanation for greater TDP retention in FM compared with the control is that the pine bark was impregnated with Fe from the micronutrient amendment (16% Fe), which subsequently increased the P adsorption capacity of the substrate. Cationization of organic materials via loading them with Fe from Fe salts has been shown to increase the P adsorption capacity of coir pith from 4.35 to 22.04 mg g$^{-1}$ P (Krishnan and Haridas, 2008) and sphagnum moss extract residue from 0.14 to 13 mg g$^{-1}$ P (Zhang et al., 2018). Both studies reported maximum P adsorption capacities at a pH of 3. Additional research is needed to investigate this possible fate of P in container substrates and whether the sorbed P is labile.

The pooled OP, TDP, and TP concentrations in FL were not different from those in the control because P concentrations in FL were initially lower (14 DAI) and eventually higher (77 and 91 DAI) than those in the control. At 14 DAI, the predicted precipitation of MnHPO$_4$ was greater in FL than in the control, suggesting that precipitation of TDP with Mn may have contributed to the initially lower pore-water P concentrations in FL. Adsorption or surface precipitation of TDP

\begin{table}
\centering
\begin{tabular}{cccccccccccc}
\hline
Time (d) & 14 & 35 & 42 & 48 & 56 & 63 & 70 & 77 & 84 & 91 \\
\hline
\textbf{Control} & 0.9 d* & 1.0 b* & 1.0 c* & 1.0 c* & 1.3 e* & 1.1 d* & 1.0 b* & 0.7 b* & 0.5 c* & 0.2 c* \\
\textbf{FL} & 2.2 b* & 1.2 b* & 1.7 b* & 1.7 b* & 1.7 b* & 1.9 b* & 2.1 a* & 1.8 a* & 1.4 ab* & 1.2 a* \\
\textbf{FM} & 1.5 c* & 1.4 b* & 1.4 b* & 1.5 b* & 1.5 b* & 1.2 b* & 1.1 b* & 0.9 bc* & 0.5 bc* & 0.1 bc* \\
\textbf{FLM} & 3.0 a* & 2.7 a* & 2.5 a* & 2.5 a* & 2.6 a* & 2.5 a* & 2.5 a* & 2.0 a* & 1.8 a* & 1.0 ab* \\
\hline
\textbf{P} & <0.0001 & <0.0001 & <0.0001 & <0.0001 & <0.0001 & <0.0001 & <0.0001 & <0.0001 & <0.0001 & 0.0007 \\
\hline
\end{tabular}
\caption{Saturation indices calculated by Visual MINTEQ for phosphorus (P) species saturated with regard to the solid phase (means >0) in pour-through extracts from pine bark substrates.} \label{tab:SI}
\end{table}
When comparing pooled TDP concentrations (2004; Xu et al., 2014; Yuan et al., 2015)

shown to have a P sorption capacity ranging onto the dolomite mineral surface may have
also had a role in the initial (14 DAI) TDP retention in FL because dolomite has been
shown to have a P sorption capacity ranging from 4.8 to 52.9 mg·g⁻¹ P (Karaca et al., 2004; Xu et al., 2014; Yuan et al., 2015). When comparing pooled TDP concentrations in FL to those in FLM, lower TDP concentrations in FLM were partially due to relative differences in P amounts absorbed by plants,
Ogden et al. (1987), who reviewed chemical properties of pine bark substrates. Damaged CRF granules have been shown to release an immediate supply of soluble P (Hue and Morris, 1999); however, this was not likely the case in the current study because damaged CRF granules were avoided when weighing CRF for each plant. In addition, extra caution was taken when incorporating the CRF in the pine bark to avoid marring the polymer coating.

Conclusion

Amending pine bark with a combination of 0.89 kg·m⁻³ micronutrients and 2.97 kg·m⁻³ dolomite reduced water-extractable OP, TDP, and TP concentrations by 56% to 58% without negatively impacting containerized crape myrtle growth or P uptake. Orthophosphate, the bioavailable form of P, contributed 75% to 89% of TP. We deduced that amending pine bark with dolomite and micronutrients reduces P leaching in open-air nursery production because pour-through and saturated media extract nutrient values. HortScience 39:1635–1639.


