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 phosphorous (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} micronutrients (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 pore-water 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 ($MnHPO_4$), 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 palygorksite 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 [$CaMg(CO_3)_2$] 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-fertilized pine bark substrate after the first five 2.6-cm irrigation events. The authors also reported that on day 48 of daily irrigation (totaling ≈125 cm of applied tap water), OP concentrations in leachate were at least 50% lower in pine bark amended with both dolomite and micronutrients compared with nonamended pine bark. In addition to reducing P runoff from container nursery sites, conventional dolomite and micronutrient amendments added to soilless substrate may improve the PUE of container-grown crops because P is retained in the root zone. In contrast to soils, pine bark substrates have no appreciable source of labile P to resupply pore-water with OP during root uptake. However, 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 PO_4-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., ≈2.6 cm·d^{-1}) fallow pine bark 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: to 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.

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., 2003).

Pine bark elemental analysis	
N (%)	0.31
P (%)	0.01
K (%)	0.10
Ca (%)	0.23
Mg (%)	0.05
S (%)	0.04
B (mg·kg^{-1})	4.3
Fe (mg·kg^{-1})	1,184.0
Mn (mg·kg^{-1})	79.3
Cu (mg·kg^{-1})	6.9
Zn (mg·kg^{-1})	27.5
C:N	189

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^{-1} (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) (Warncke, 1986) contained (in mg·L^{-1} ± SE) less than 0.31 NH_4-N, less than 0.12 NO_2-N, 0.12 ± 0.02 NO_3-N, 7.67 ± 0.46 PO_4-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 ± 0.041 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% $CaCO_3$ 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 $CaMg(CO_3)_2$, $FeSO_4{\cdot}1H_2O$, $MnSO_4$, $ZnSO_4$, $CuSO_4{\cdot}5H_2O$, $Na_2B_4O_7$, and $Na_2MoO_4{\cdot}2H_2O$. Incorporation of dolomite and micronutrients into the substrate was accomplished by mixing for 5 min using a small cement mixer (0.14 m^3 capacity; ≈23 rotations per minute). Five 11.4-L aliquots of each of the four substrate mixes were amended with 28 g

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(i.e., 2.97 kg·m^{-3} pine bark) of a polymer-coated 19N–2.6P–10.8K CRF (Harrell's LLC, Lakeland, FL). The CRF was a homogeneous 3- to 4-month release formulation (at 27 °C) in which N, P, and K were derived from NH_4NO_3, $NH_4H_2PO_4$, and K_2SO_4. The 20 substrate aliquots were each hand-mixed for 2 min to ensure equal distribution of CRF without damaging granules. The entirety of each aliquot of CRF-amended pine bark was then added to 20 respective 11.4-L black plastic containers (C1200; Nursery Supplies, Chambersburg, PA) to plant one crape myrtle liner per container. During potting, the existing substrate was left in the liner root balls to minimize transplant stress. Plants were then hand-watered until leaching was observed.

Plants were grown for 93 d on four 353 × 97 × 76 cm (l × w × h) benches (five plants per bench) that each ran south to north in an environmentally controlled glass greenhouse with 80% photosynthetically active radiation transmission. Average daily maximum and minimum air temperatures measured using a digital temperature and humidity sensor (AcuRite 00619HD; Chaney Instrument Co., Lake Geneva, WI) were 25.4 ± 0.46 °C and 14.2 ± 0.39 °C, respectively. Plants on the same benchtop were spaced ≈37 cm and benches were ≈46 cm apart. A randomized complete block design (RCBD) with four substrate treatments and five blocks was used to account for possible temperature and shading variations within the greenhouse caused by cooling pads. Blocks were arranged across benches south to north, with blocks 1 and 5, respectively, furthest from and closest to the cooling pads.

To monitor the substrate temperature, a digital meat thermometer (AcuRite 00641W; Chaney Instrument Co.) with a 12.3-cm probe was inserted horizontally through the container wall ≈11 cm above the container bottom of a randomly selected plant in blocks 1, 3, and 5. Thermometers remained in the same three containers for the entirety of the study with the tip of each probe approximately in the center of the horizontal substrate profile. The substrate temperature was recorded on pour-through sampling dates before irrigation. The average substrate temperature, before irrigating, was 21.0 ± 0.5 °C over the course of the study.

Plants were monitored weekly for signs of pests and diseases. On day 8, all plants received ≈600 mL of cyantraniliprole (Mainspring GNL; 0.793 mL·L^{-1}) drench to prevent infestation of common greenhouse pests (e.g., thrips, whitefly, scale). Fungus gnat larvae were controlled at 48 d after experiment initiation (DAI) by releasing 75,000 predatory mites (*Hypoaspis miles*; Biobest Sustainable Crop Management, Westerlo, Belgium) evenly divided among the 20 plants on the substrate surface.

Irrigation was controlled with GEVA 75 irrigation window controllers, each with a latch solenoid and hydraulic valve (G75-C-1W-61; Baccara Automation Control, Bayswater, Victoria, AU), and applied via pressure-compensating spray stakes (202 mL·min^{-1}) (01PSDS-PL1-B; Netafim, Fresno, CA). Plants received cyclic irrigation (two cycles per day; ≈3 min between cycles) with tap water every 4 to 7 d until 63 DAI, and then every 2 to 3 d for the remainder of the study based on need. An additional pressure-compensating spray stake of the same flow rate was added to all containers at 20 DAI to improve moisture distribution uniformity within each container. The irrigation volume was adjusted periodically as needed to achieve a target weekly leaching fraction (volume leached/volume applied) of 0.20. The observed average leaching fraction, measured weekly, was 0.20 ± 0.009 (n = 264) over the course of the study. Element concentrations in irrigation water were stable over time, with the following mean (n = 10) values (mg·L^{-1} ± SE): 13.0 ± 0.38 Ca; 1.3 ± 0.08 K; 5.4 ± 0.17 Mg; 10.3 ± 0.22 Na; 0.1 ± 0.02 Fe; 0.4 ± 0.01 mg·L^{-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^{-1} and 0.15 ± 0.002 mS·cm^{-1}, respectively.

Irrigation preceding pour-through extraction 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 irrigation 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 deionized (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 sample was analyzed for pH and EC within 4 h of pour-through extraction. The remainder of each sample was divided, prepared, and analyzed for ions, total dissolved (<0.45 µm) elements, dissolved organic carbon (DOC), and total (nonfiltered) element concentrations 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 remaining. 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, summed 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 Laboratories (New Bremen, OH) for tissue nutrient analysis, during which plant samples were analyzed using a Thermo 6500 Duo ICP-OES (Thermo Fisher Scientific, Weltham, MA) after microwave-assisted digestion with nitric acid and hydrogen peroxide (T002 test package). Tissue nutrient concentrations were multiplied by the SDW or RDW values to calculate the P content. The total tissue P content (i.e., the sum of the 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 postexperiment 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 volumes of each of the 20 postexperiment CRF samples as well as five 2-g samples of fresh CRF were determined by submerging granules in 5 mL of DI water contained in a 10-mL graduated cylinder and measuring displaced 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 polyvinylidene fluoride (PVDF) filter diluted 90% with DI water and then analyzed for NO_3, NO_2, NH_4, PO_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_4, NO_3, PO_4, and K, respectively, remained in the CRF at the end of the experiment, and no differences were observed among substrate treatments.

Visual MINTEQ (Gustafsson, 2013) was used to model chemical P speciation in leachate. Input parameters included pH, DOC (NICA-Donnan model), PO_4^{3-}, NH_4^+, NO_2^-, NO_3^-, B(III), Ca^{2+}, Cl^-, Cu^{2+}, Fe^{3+}, K^+, Mg^{2+}, Mn^{2+}, Mo(VI), sodium (Na^+), Ni^{2+}, SO_4^{2-}, and Zn^{2+} concentrations. Metals were assumed to be in their oxidized state. Carbonate (CO_3^{2-}) concentrations were estimated based on the measured irrigation water alkalinity as well as Ca and Mg concentrations in leachate of substrates containing dolomite and/or micronutrients as an indicator of $CaMg(CO_3)_2$ dissolution.

Saturation index (SI) values were used to interpret the degree of saturation in solutions with regard to solid phases. Saturation indices were calculated as $\log(IAP/K_{sp})$, where IAP is the ion activity product and K_{sp} 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 heterogenous covariance structures available in JMP Pro 14 (SAS Institute Inc., Cary, NC) and subsequently comparing corrected Akaike information criterion (AIC_c) values. According to lowest AIC_c 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 KaleidaGraph 4.5.3 (Synergy Software, Reading, PA).

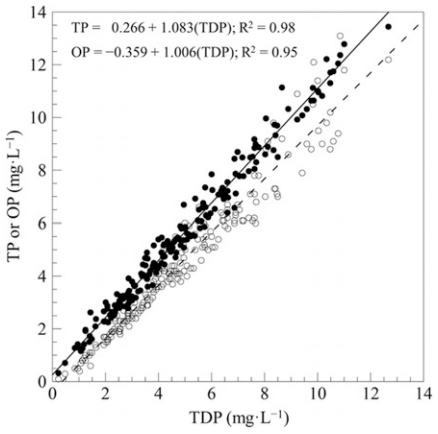

Fig. 1. Linear relationship between total dissolved phosphorus (TDP) and total phosphorus (TP; filled circles) or orthophosphate phosphorus (OP; open circles) in pour-through extracts collected approximately weekly for 91 d from containerized *Lagerstroemia* 'Natchez' grown in pine bark with 2.97 kg·m^{-3} of a polymer-coated 19N–2.6P–10.8K controlled-release fertilizer and one of the following amendment treatments: no amendments (control); 2.97 kg·m^{-3} dolomite (FL); 0.89 kg·m^{-3} micronutrient fertilizer (FM); or both dolomite and micronutrient fertilizer (FLM). Equations were developed from data pooled across time and substrate treatments (n = 198).

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 TDP (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 to

Table 2. Degrees of freedom (df), F-values, and *P* values for the analysis of variance (ANOVA) to determine significant effects of substrate treatment, time (1 to 91 DAI), and the substrate × time interaction on orthophosphate phosphorus (OP) total dissolved phosphorus (TDP), particulate phosphorus (PP), total phosphorus (TP), pH, calcium (Ca), and manganese (Mn) in pour-through extracts of container-grown *Lagerstroemia* 'Natchez'. Substrates were amended with 2.97 kg·m^{-3} of a polymer-coated 19N–2.6P–10.8K controlled-release fertilizer (CRF) and either 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).

ANOVA source	df	F value	*P* value
OP			
Substrate	3	27.9	<0.0001
Time	9	49.6	<0.0001
Substrate × time	27	7.3	<0.0001
TDP			
Substrate	3	24.5	<0.0001
Time	9	32.1	<0.0001
Substrate × time	27	3.8	<0.0001
PP			
Substrate	3	3.1	0.0508
Time	9	12.3	<0.0001
Substrate × time	27	2.2	0.0063
TP			
Substrate	3	23.2	<0.0001
Time	9	44.4	<0.0001
Substrate × time	27	5.0	<0.0001
pH			
Substrate	3	3,506.4	<0.0001
Time	9	30.6	<0.0001
Substrate × time	27	15.6	<0.0001
Ca			
Substrate	3	188.9	<0.0001
Time	9	24.9	<0.0001
Substrate × time	27	13.0	<0.0001
Mn			
Substrate	3	525.1	<0.0001
Time	9	49.9	<0.0001
Substrate × time	27	10.3	<0.0001

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 phosphorous (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).

Substrate	OP (mg·L^{-1})	TDP (mg·L^{-1})	PP (mg·L^{-1})	TP (mg·L^{-1})	SDW (g)	RDW (g)	TDW (g)	Tissue P (mg)	PUE[z]
Control	5.8 a[y]	6.2 a	0.70	7.4 a	49.9 b	13.1 b	62.9 b	199.2 ab	0.30
FL	6.1 a	6.4 a	0.85	6.9 a	36.3 c	8.9 b	45.1 c	164.6 b	0.25
FM	3.7 b	4.2 b	0.53	4.7 b	65.4 a	21.4 a	86.8 a	194.2 ab	0.29
FLM	2.5 b	2.7 c	0.58	3.3 c	76.9 a	18.3 a	95.3 a	210.8 a	0.33
P value	<0.0001	<0.0001	0.0508	<0.0001	<0.0001	<0.0001	<0.0001	0.0188	

[z]PUE = (mg P in plant tissue) ÷ (mg P released from CRF).
[y]Means followed by the same letter within columns are not significantly different according to Tukey's honestly significant difference (0.05).

determine if relatively high PP concentrations corresponded with relatively low TDP concentrations. Particulate P and TDP concentrations had a moderate positive correlation ($r = 0.471$; $P < 0.0001$). Similar to TDP, 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 × 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 FM 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 manganese hydrogen phosphate ($MnHPO_4$) and hydroxyapatite [$Ca_5(PO_4)_3OH$] (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 in the control or FM substrates. Saturation indices for $Ca_5(PO_4)_3OH$ in FL were greater than 0 and generally higher than SI values in FLM from 42 to 70 DAI. In FLM, SI values for $Ca_5(PO_4)_3OH$ were greater than 0 only at 70 DAI. In extracts from the control and FM, the $Ca_5(PO_4)_3OH$ 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 $Ca_5(PO_4)_3OH$ solid phases. Because the substrate and time main effects and the substrate × 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 × time interaction for pH, pore-water pH varied by ≤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 ± 0.02, 6.4 ± 0.03, 3.7 ± 0.02, and 6.2 ± 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 ≈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

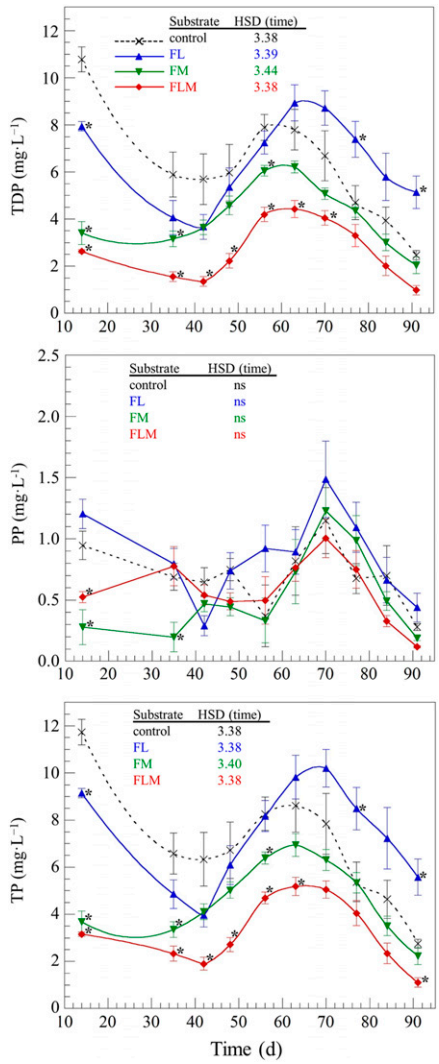

Fig. 2. Effects of substrate treatments on total dissolved phosphorus (TDP), particulate phosphorus (PP), and total phosphorus (TP) concentrations over time in pour-through extracts of containerized *Lagerstroemia* 'Natchez' grown for 91 d in a pine bark substrate amended with 2.97 kg·m^{-3} of a polymer-coated 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.

Table 4. Saturation indices calculated by Visual MINTEQ for phosphorus (P) species saturated with regard to the solid phase (means >0) in pour-through extracts collected at various times over the course of 91 d from containerized *Lagerstroemia* 'Natchez' grown 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). In addition to CRF, substrate treatments included the following: 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).

	Time (d)									
	14	35	42	48	56	63	70	77	84	91
	Saturation index									
$MnHPO_4$										
Control	0.9 d[z]*	1.0 b*	1.0 c*	1.0 c*	1.3 c*	1.1 d*	1.0 b*	0.7 b*	0.5 c*	0.2 c*
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*
FM	1.5 c*	1.4 b*	1.4 bc*	1.5 b*	1.7 b*	1.5 c*	1.2 b*	1.1 b*	0.9 bc*	0.5 bc*
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*
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0007
$Ca_5(PO_4)_3(OH)$										
Control	–16.1 b	–15.1 b	–15.3 c	–15.5 c	–13.9 c	–14.5 c	–15.1 b	–15.6 b	–17.1 b	–18.0 c
FL	–0.9 a	0.1 a	0.8 a*	0.9 a*	1.2 a*	1.1 a*	1.5 a*	0.4 a	–0.3 a	–1.6 a
FM	–16.2 b	–16.5 c	–16.4 d	–16.4 c	–15.1 d	–15.8 d	–16.7 b	–16.8 b	–18.1 b	–19.6 d
FLM	–0.7 a	–0.4 a	–0.8 b	–1.1 b	–0.2 b	–0.4 b	1.6 a*	–0.2 a	–0.2 a	–4.6 b
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[z]Means followed by the same letter within columns are not significantly different according to Tukey's honestly significant difference (0.05).
*Indicates significantly >0 at the 0.05 level according to a one-sample *t* test with the hypothesized mean set to "0".

grown in FLM compared with FL, and equivalent among plants grown in the control, FM, or FLM substrates. Because CRF-P release was the same across treatments, the effects of treatments on PUE were interpreted in the same way as those of tissue P content, with the highest PUE in plants grown in the control, FM, and FLM and lowest in those 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 ≈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: TDP = 0.237 + 1.03(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 × 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. (2007 b) reported a similar relationship between OP and TP in runoff samples from container-grown *Viburnum odoratissimum* (L.) Ker-Gawl: TP = 0.03 + 1.10(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 pour-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 $Ca_5(PO_4)_3OH$ 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} (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

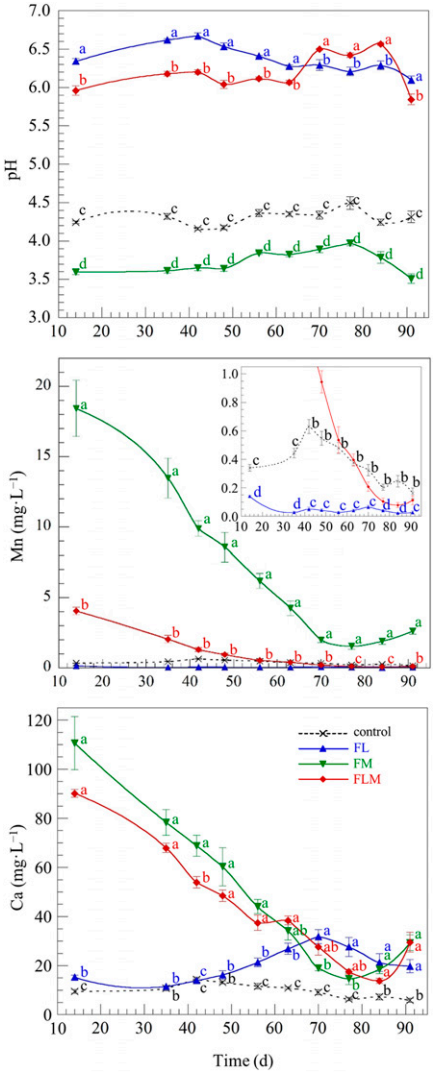

Fig. 3. Effects of substrate treatments on pH, manganese (Mn), and calcium (Ca) over time in pour-through extracts of containerized *Lagerstroemia* 'Natchez' grown for 91 d in a pine bark substrate amended with 2.97 kg·m^{-3} of a polymer-coated 19N–2.6P–10.8K controlled-release fertilizer (CRF). Substrate treatments included the following: 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). Different vertically aligned letters next to means indicate significant difference among substrate treatments (control, FL, FM, and FLM) within the corresponding sampling date according to Tukey's honestly significant difference (HSD) ($n = 5$; $P < 0.01$). Nontransformed values are reported. Vertical bars represent the SEM.

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, as indicated by the 28% higher tissue P amounts in plants grown in FLM compared with FL.

Because the tissue P content in FM was the same as that in FLM, the lower pore-water TDP concentrations in FLM were not a result of differences in plant uptake of P. Saturation indices for $MnHPO_4$ in FLM were 55% to 103% higher than those in FM at all sampling dates; hence, a greater degree of $MnHPO_4$ precipitation is one possible explanation for lower pore-water TDP concentrations in FLM compared with FM. Because SI values for $Ca_5(PO_4)_3OH$ were positive only at one of the 10 sampling dates, the precipitation of $Ca_5(PO_4)_3OH$ was unlikely a sink for TDP in FLM. In contrast, Shreckhise et al. (2019) reported SI values of as high as 7.3 for $Ca_5(PO_4)_3OH$ in leachate from fallow pine bark columns containing dolomite and micronutrient amendments. The lower SI values for $Ca_5(PO_4)_3OH$ in the current study were likely a result of lower pH values; in the current study, the pH was ≈6.2, but it was >7 in another study (Shreckhise et al., 2019). As was previously mentioned for the single-amendment treatments, adsorption of TDP by dolomite or pine bark impregnated with Fe from the micronutrients also may have contributed to the lower TDP concentrations in FLM compared with those in all other substrates.

A possible explanation for equivalent P uptake among plants in FM and the control is that despite the lower concentrations of available P in substrate pore-water for plants in FM, OP concentrations were still sufficiently high that uptake was not limited. As was illustrated by Timmer (1991), increasing the supply of a limiting plant nutrient initially results in a relatively rapid increase in the plant tissue content of that nutrient until it is no longer limiting. Increasing the supply of a nonlimiting nutrient results in minor increases of that nutrient in plant tissue. In the current study, we suspect that P was nonlimiting in FM because plants grown in this substrate had higher biomass than those grown in the control. Accordingly, differences in pore-water OP concentrations among treatments expectedly had a minor impact on P tissue content. Another possible reason why plants grown in the control and FM substrates had similar tissue P content is that TDP concentrations were lower in FM than in the control only at 14, 35, and 56 DAI. Therefore, TDP concentrations in these two treatments were the same during the period when plants were largest and, therefore, expectedly had higher P absorption rates compared with those earlier in the trial (Tanaka et al., 1974; Xu et al., 2004). The effect of pH on P uptake is a third explanation for equivalent P amounts in the plant tissue of plants grown in FM or the control. The consistently lower pH values in FM (≈3.7) compared with those in the control (≈4.3) may have hindered OP uptake for plants in FM, partially offsetting the greater biomass of plants in FM compared with those in the control. Similarly, when growing six plant taxa in solution culture, Islam et al. (1980) found that tissue P concentrations increased with the increasing solution pH in the range of 3.3 to 5.5. Phosphorus uptake efficiency values in the current study (0.25–0.33) were within the range of 0.07 to 0.62 reported in other studies in which containerized woody plants were grown in a pine bark-based substrate with CRF (McGinnis et al., 2009; Owen et al., 2008; Tyler et al., 1996a, 1996b; Warren et al., 2001).

The SDW, RDW, and total dry weight data indicate that 0.89 kg·m^{-3} of the micronutrient amendment used in this study equally improves the growth of crape myrtle in limed and nonlimed pine bark substrate, whereas liming with 2.97 kg·m^{-3} dolomite limits crape myrtle growth if micronutrient fertilizer is absent. Consistent with our findings, in a review of dolomite effects on plant growth in pine bark substrate, Altland and Jeong (2016) concluded that a supplemental micronutrient fertilizer is generally necessary in substrates containing dolomite to avoid pH-induced plant micronutrient deficiency. However, the effects of micronutrient amendments on plant growth in nonlimed pine bark substrates seem to be taxa-specific when assessing results in this study and others in the literature. When growing containerized crops in a pine bark-based substrate, micronutrient fertilization reduced the growth of *Juniperus virginiana* L. (Wright and Hinesley, 1991), improved growth in nine deciduous tree species (Wright et al., 1999), and had no effect on growth of *Rhododendron* L. × 'Girards Scarlet' (Rose and Wang, 1999) compared with plants grown in substrates not amended with a supplemental micronutrient source. In the current study, the limiting nutrients responsible for reduced growth of crape myrtle grown in FL and the control could not be discerned because foliar tissue samples were not analyzed. However, weekly photographs of each plant indicated that at 70 DAI, plants within the FL treatment were visibly smaller and recently matured leaves displayed interveinal chlorosis and necrosis, indicating deficiency of nutrients with low (e.g., Ca, Mn) or intermediate (e.g., Fe, Zn, Cu, B, Mo) phloem mobility (Marschner, 2012).

The observed increase followed by a decrease in TP and TDP concentrations between 42 and 91 DAI in all substrate treatments is similar to that described by Du. et al. (2006), who assessed P release from two polyurethane-coated CRFs in silica sand. The relatively high initial pore-water TDP concentrations at 14 DAI (i.e., 9.5 ± 0.72 mg·L^{-1} P) in the F and FL treatments can be primarily attributed to indigenous P in the pine bark. The total dissolved P concentration in saturated media extracts of nonamended bark was 7.67 ± 0.46 mg·L^{-1}, which is equivalent to ≈13.7 mg·L^{-1} TDP when extracted via the pour-through method according to the calibration equation reported by Cavins et al. (2004). These observed indigenous TDP concentrations in pine bark are in line with the range of 6.9 to 9.0 mg·L^{-1} P reported by

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 (Huett 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 $kg \cdot m^{-3}$ micronutrients and 2.97 $kg \cdot m^{-3}$ 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 extract is comparable to solution leaching from nursery containers from irrigation. Therefore, amending pine bark-based substrates with dolomite and micronutrients may be a best management practice for reducing P in nursery runoff when crop growth is improved or unchanged by their addition. Further consideration should be given to the abundance of P-reactive elements (e.g., Mn, Fe, Ca) in routinely applied irrigation water that could further affect P chemistry and subsequent plant availability. For example, the consistent presence of supersaturated $MnHPO_4$ solid phases in substrate pore-water suggests that Mn in irrigation water could limit P availability, especially in limed substrate.

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