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RESEARCH

Phosphorus Requirements of St. Augustinegrass Grown in Sandy Soils

Min Liu, J.B. Sartain,* L.E. Trenholm, and G.L. Miller

ABSTRACT

Phosphorus fertilization of St. Augustinegrass [*Stenotaphrum secondatum* (Walt.) Kuntze] is performed on the basis of soil tests designed for agronomic crops. The objectives of this study were to determine the critical minimum P application rate and soil and tissue P concentration of St. Augustinegrass grown in sandy soils. Three studies were conducted in a glasshouse using a Pomona sand, two Tavares sands, and a Pottsburg sand. Established pots of 'Floratam' St. Augustinegrass received P at 0, 0.14, 0.27, 0.54, and 1.09 g m^{-2} every four weeks for 16 weeks for Study 1 and 12 weeks for Studies 2 and 3. Critical minimum tissue P concentration was determined to be 1.8 g kg^{-1} on dry weight basis. Minimum P application rate was 0.14 g m^{-2} 4-wk^{-1} to obtain acceptable turfgrass quality and growth rate. Additional growth was not observed when Mehlich-1 P level was greater than 7, 8, 9, and 5 mg kg^{-1} for Pomona sand, Tavares sand (a), Pottsburg sand, and Tavares sand (b), respectively. Phosphorus fertilization would not be recommended if soil Mehlich-1 P concentration is above 10 mg kg^{-1} for sandy soils or tissue P level is beyond 1.8 g kg^{-1} on dry weight basis. Phosphorus application of 0.14 g m^{-2} 4-wk^{-1} is recommended when P is required.

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St. Augustinegrass [*Stenotaphrum secondatum* (Walt.) Kuntze] is a popular choice for lawns throughout the southern United States. It is believed to be native to the Caribbean, African and Mediterranean regions, and best adapted to subtropical climates. It grows best in full sun and long daylength, but most cultivars have a high tolerance for shade compared to other warm-season turfgrasses. St. Augustinegrass grows quickly during the summer months, but slows during the spring and fall and may enter a dormancy period during the winter months if temperatures drop below freezing. Due to poor wear tolerance, St. Augustinegrass is used primarily for lawns and general purpose turf, but not for high traffic sports turf (Trenholm et al., 2006). It can grow satisfactorily in a wide variety of soils (Trenholm et al., 2006). St. Augustinegrass requires moderate to high nitrogen fertilization to maintain good visual quality and vigor, with recommendations for other nutrient fertilization based on soil test results (Trenholm et al., 2006).

The most essential function of P in plants is energy storage and transfer. Phosphorus is also an important structural component of nucleic acids, coenzymes, nucleotides, phosphoproteins, phospholipids, and sugar phosphates. Phosphorus plays an essential role in plants; therefore, total elimination of P fertilization due to environmental concerns is not justified. Plants absorb

Published in Crop Sci. 48:1178–1186 (2008).
doi: 10.2135/cropsci2007.09.0506
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either $H_2PO_4^-$ or HPO_4^{2-} orthophosphate ions (Havlin et al., 1999). Plant tissue P concentration ranges between 1 and 5 g kg^{-1} (Havlin et al., 1999). Phosphorus ion concentration in soil solution ranges between 0.03 and 0.5 mg kg^{-1} in most soils (Ozanne, 1980; Mengel and Kirkby, 1987; Raghothama, 1999; Frossard et al., 2000). In general, it is believed that a soil solution P concentration of 0.2 mg kg^{-1} is adequate for most crops. Phosphorus exists in soil solution primarily in anionic forms and the distribution among various species (H_3PO_4, $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-}) in solution is governed by solution pH. In the pH domain of most soils the dominant orthophosphate ions are $H_2PO_4^-$ and HPO_4^{2-}, the latter being the major species at pH above 7.2 (Lindsay, 1979).

Phosphorus is a macronutrient, therefore, it is often included in fertilizer regimes. Phosphorus enters into many inorganic forms in the natural setting, which renders it less soluble by precipitation and adsorption. While P is not typically prone to leaching, many Florida soils are sandy and acidic, which may allow significant P leaching. The P leaching potential of acidic uncoated sand soil is much greater than an Fe oxide coated sandy soil (Snyder et al., 2000). Additionally, shallow groundwater intercepted by drains allows leached P to enter surface water bodies. This may result in eutrophication of surface waters, which is caused by a surplus of available nutrients, particularly N and P. Eutrophication may result in a decrease in dissolved oxygen in waterways leading to a decline in the eco-system. For this reason, P fertilization of lawn grasses needs to precisely meet the P requirement of the turfgrass without ending up as runoff or leachate.

In practice, recommendations for P fertilization rely primarily on a soil P test, or, to a lesser extent, on tissue tests. Most soil P extractants were developed to estimate the capacity of the soil to supply P. They were designed to extract some fraction of the labile P and thus provide an index of the availability of P to plants over the growing season. Mehlich-1 extractant is used widely in the southeastern United States. It is a solution containing 0.05 M HCl and 0.0125 M H_2SO_4 (Mehlich, 1953). Very little information has been documented concerning the P requirement of St. Augustinegrass. Wood and Duble (1976) found that St. Augustinegrass responded to P application in extremely low P soils only during the first eight weeks of establishment. The critical minimum tissue P concentration of St. Augustinegrass was reported to be 1.6 g kg^{-1} by Liu et al. (2006) in a glasshouse solution culture study. Literature relative to the critical minimum soil test P concentration of St. Augustinegrass was not found. At present P fertilization of Florida lawn grasses is based on soil tests that were designed for agronomic crops in production culture. The objectives of this study were to determine the critical minimum P application rate, the critical minimum tissue P concentration, and the critical minimum Mehlich-1 P concentration in soil for St. Augustinegrass to achieve optimum growth and turf quality.

MATERIALS AND METHODS

Three individual studies were conducted in glasshouses on four sandy soils [one Pomona sand (Sandy, Siliceous, Hyperthermic Ultic Alaquods), two Tavares sands (Hyperthermic Uncoated Typic Quartzipsamments), and one Pottsburg sand (Sandy, Siliceous, Thermic Grossarenic Alaquods)]. The chemical properties of the soils used in these studies are shown in Table 1. The Pomona sand used in Study 1 and the Tavares sand and Pottsburg sand used in Study 2 were low in Mehlich-1 P concentrations (≤5 mg kg^{-1}). The Tavares sand used in Study 3 contained a medium level of Mehlich-1 P concentration (17 mg kg^{-1}). Soils used were collected from the A horizons. These glasshouse soil studies were conducted at the Turfgrass Envirotron at the University of Florida, Gainesville, Florida. Nalgene tubs (53 cm × 38 cm × 12 cm) were used as growth containers. Outside surfaces of the containers were painted with white latex paint first and black afterward to prevent light penetration. Certified sod with high initial tissue P concentration was washed to remove soil, then cut to a size of 53 cm × 38 cm and transferred to the growth container. Computer controlled overhead fans, a wall-length humidifier, and an automatic roof window were used to maintain relatively constant conditions in the glasshouse. Glasshouse temperature was maintained at an average 24°C with a range of 18°C to 30°C. The relative humidity was maintained at about 75%.

After tissue P levels were reduced to less than 1.2 g kg^{-1}, P deficiency was induced. Phosphorus as concentrated superphosphate (CSP) was applied at 0, 0.14, 0.27, 0.54, and 1.09 g m^{-2} 4-wks^{-1}. For Study 1, treatments were initially applied on 8 May 2005 and reapplied three times during the 16-wk growth period; for Study 2, treatments were initially applied on 20 June 2006 and reapplied twice during the 12-wk growth period; for Study 3, treatments were initially applied on 8 August 2006 and reapplied

Table 1. Selected chemical properties of soils used in glasshouse soil P studies.

Soil study	Soil no.	Classification	Series	pH (1:2)†	OM‡	Mehlich-1 P	Oxalate Al§	Oxalate Fe§
					g kg^{-1}	——mg kg^{-1}——		
1	1	Sandy, siliceous, hyperthermic Ultic Alaquods	Pomona	4.6	9	2	32	42
2	2	Hyperthermic uncoated Typic Quartzipsamments	Tavares (a)	5.1	15	3	77	60
	3	Sandy, siliceous, Thermic Grossarenic Alaquods	Pottsburg	4.7	9	5	49	27
3	4	Hyperthermic uncoated Typic Quartzipsamments	Tavares (b)	4.8	13	17	173	154

†Soil pH was determined in 1:2 soil/water ratio.

‡Organic matter content was determined by loss on ignition.

§Determination of oxalate Al and Fe were performed as described by Mckeague and Day (1966).

twice during the 12-wk growth period. Treatments in Studies 1 and 3 were arranged in a completely randomized design with five rates of P application. Treatments in Study 2 were arranged in a 2 by 5 factorial design with two soils and five rates of P application. Each treatment was replicated five times.

Top growth was clipped to 7.5 cm every other week. Clippings were dried at 70°C for 72 h, and weighed. Tissue growth rate was calculated by dividing tissue dry weight by growth days. The dry tissue samples were ground to 2 mm and ashed. Samples were analyzed for P by spectrophotometry using the molybdenum-reduced molybdophosphoric method (Hanlon et al., 1994). Turf visual quality was rated weekly using a scale of 1 to 9, where 1 represents brown, dormant turf and 9 represents superior quality (Skogley and Sawyer, 1992). A turf quality value of 5.5 is considered to be a minimum for acceptable quality.

Soil samples were taken at termination using a 3-cm diameter soil probe. Nine soil cores were taken for each container. Soil samples were separated into soil depths of 0 to 2 cm and 2 to 10 cm. Soil samples were air-dried at room temperature. Mehlich-1 extractable P was determined for the soil samples in depth of 0 to 2 cm and 2 to 10 cm.

Analysis of variance was performed by SAS (SAS Institute, 1987). Duncan's multiple range test was used for the mean separation in Studies 1 and 3, which were completely randomized designed; Tukey's test was used for the mean separation in Study 2, which was a factorial design. Means marked by the same letter are not significantly different at $P = 0.05$.

RESULTS AND DISCUSSION

Turf Quality

For the Pomona sand in Study 1, the highest P application of 1.09 g m^{-2} 4-wk^{-1} resulted in the best turf quality (Table 2). There was no difference in turf quality associated with the highest P rate and the second highest P rate except for the first week (Table 2). The third highest P application rate also achieved the best turf quality, except for the first three weeks (Table 2). Averaged over the trial period, best quality resulted in application of the two highest P rates. With the P deficiency induced for St. Augustinegrass before P application, it took up to four weeks for St. Augustinegrass to recover from the P deficiency after P application. The higher the P rates applied, the shorter the time required for the turfgrass to recover and produce the best quality. The second lowest P application of 0.14 g m^{-2}

Table 2. Visual quality rating of St. Augustinegrass as influenced by P application rate and soil series.

Soil	P rates	Week†																Mean
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
	g m^{-2} 4 wk^{-1}																	
	0	6.4c	6.5c	5.9c	7.0b	6.7b	6.8b	6.6b	6.9c	6.2b	6.2b	5.7c	5.4b	5.4b	6.1b	4.5b	4.6b	6.3c
	0.14	7.0b	7.4ab	7.3b	7.4ab	7.3a	7.5a	7.4a	7.4bc	7.2a	7.7a	7.3b	7.6a	7.2a	7.9a	7.1a	7.4a	7.4b
Pomona	0.27	6.9b	7.3b	7.2b	7.6ab	7.2a	7.7a	7.2ab	7.6ab	7.2a	7.6a	7.5ab	7.7a	7.0a	7.9a	7.5a	7.4a	7.4b
Sand	0.54	6.9b	7.7ab	7.7ab	7.8a	7.6a	7.8a	7.6a	7.9ab	7.6a	8.0a	7.8ab	7.8a	7.5a	8.1a	7.5a	7.7a	7.7ab
	1.09	7.4a	8.0a	8.1a	8.0a	7.8a	8.1a	7.8a	8.1a	7.7a	8.1a	8.0a	8.0a	7.8a	8.2a	7.6a	7.9a	7.9a
CV(%)		4.3	6.3	6.4	7.4	6.1	5.6	6.3	5.5	6.2	5.9	6.1	4.8	8.7	6.9	6	8.8	4.7
	0	6.5a	6.7b	6.4a	5.7b	5.3b	5.5b	4.7b	4.5b	4.7c	4.5b	5.0b	4.4b					5.3b
	0.14	7.3a	7.8ab	7.3a	7.6a	6.9a	7.3a	6.3a	6.8a	6.6b	7.4a	6.5a	6.8a					7.0a
Tavares	0.27	6.9a	7.6ab	7.3a	7.4a	7.2a	7.5a	6.8a	7.1a	7.3a	7.6a	6.6a	7.0a					7.2a
Sand (a)	0.54	7.3a	8.1a	7.3a	7.6a	7.4a	7.7a	7.1a	7.2ab	7.3a	8.0a	7.0a	7.1a					7.4a
	1.09	7.1a	7.8a	7.5a	7.7a	7.4a	7.8a	7.4a	7.4a	7.3a	7.6a	7.1a	7.0a					7.4a
	0	6.5a	6.7b	6.3b	5.4c	5.1b	5.3b	4.2b	4.2b	4.3b	4.5b	4.7b	4.5b					5.1b
	0.14	6.9a	7.4ab	7.1ab	6.8b	6.0ab	6.6ab	6.2a	6.6a	6.1a	6.9a	6.7a	6.2a					6.6a
Pottsburg	0.27	6.8a	7.6ab	6.5ab	7.1ab	6.3ab	6.8a	6.1a	6.4a	6.9a	7.5a	6.2a	6.6a					6.7a
Sand (a)	0.54	7.0a	7.6ab	7.4ab	7.4ab	7.0a	7.5a	6.8a	7.1a	7.1a	7.4a	6.9a	6.8a					7.2a
	1.09	7.3a	8.1a	7.7a	7.8a	7.4a	8.0a	7.3a	7.3a	7.4a	7.7a	7.2a	7.0a					7.5a
CV(%)		5.7	8	9.1	6.7	10.7	9.9	6.8	6.8	8.6	6.6	10.1	7.5					6.3
	0	6.1b	6.2b	5.8b	5.6c	5.5b	5.2b	5.6b	5.4b	6.3b	6.9c	6.9c	6.6b					6.2b
	0.14	7.2a	7.5a	6.6ab	7.1b	7.1a	7.1a	7.1a	6.6a	6.9ab	7.1bc	6.8bc	7.1a					7.0a
Tavares	0.27	7.5a	7.9a	7.1a	7.7ab	7.5a	7.2a	7.2a	7.2a	7.4a	7.6abc	7.3ab	7.3a					7.4a
Sand (b)	0.54	7.6a	7.9a	7.5a	7.8a	7.6a	7.7a	7.2a	7.3a	7.4a	7.7ab	7.5a	7.4a					7.6a
	1.09	7.7a	8.0a	7.6a	7.6ab	7.6a	7.5a	7.3a	7.3a	7.2a	7.9a	7.5a	7.4a					7.5a
CV(%)		7.6	4.9	10.7	6.8	7.6	9.7	5.4	8.3	8.8	7.4	6.5	5.2					5.7

†Within columns for each soil, means followed by the same letter are not significantly different according to Duncan's Multiple Range Test for Pomona sand (Study 1) and Tavares sand (b) (Study 3) and Tukey's Test for Tavares sand (a) and Pottsburg sand (Study 2).

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4-wk^{-1} resulted in the equivalent best turf quality in 12 out of 16 weeks (Table 2), which provided evidence that the minimum P application rate was approximately 0.14 g m^{-2} 4-wk^{-1} for Pomona sand. The turf quality of the control treatment remained above 6.0 for the first 10 weeks and started to decline afterward. By the last two weeks the turf quality was below 5.5, which is widely used as a minimum value for acceptable turf quality. Overall, turf quality ratings were acceptable, except for the control treatments during the last four weeks. This suggests that St. Augustinegrass could be sustained for months with very low soil P concentrations.

For the Tavares sand (a) and Pottsburg sand in Study 2, quality ratings were influenced by P application rate as shown in Table 2. Twelve weeks of turf quality data were collected. Phosphorus application of 0.14 g m^{-2} 4-wk^{-1} achieved the best turf quality in 11 out of 12 weeks for both soils (Table 2), which provided evidence that the minimum P application rate was approximately 0.14 g m^{-2} 4-wk^{-1} for these two soils. For the control turf, turf quality remained above the acceptable level of 5.5 for the first four and three weeks for Tavares sand and Pottsburg sand, respectively, and declined afterward. Turf with no P application did not recover from an incidence of insect (scale), which suggests the importance of P nutrition in case of insect damage recovery.

For the Tavares sand in Study 3, the quantity of applied P influenced St. Augustinegrass quality (Table 2). A P application of 0.14 g m^{-2} 4-wk^{-1} resulted in the equivalent best turf quality in 10 out of 12 weeks (Table 2). Duncan's multiple range test of turf quality rating versus rate of P applied revealed differences in mean turf quality rating up to 0.14 g m^{-2} 4-wk^{-1}. Application of additional P beyond 0.14 g m^{-2} 4-wk^{-1} did not increase turf quality. The previous glasshouse Studies 1 and 2 reported the same response to P application for St. Augustinegrass growing in coarse textured sandy soils. The overall turf quality including controls was generally good, possibly because the relatively sufficient labile soil P prevented severe P deficiency on St. Augustinegrass. The soil used in this study initially contained 17 mg kg^{-1} Mehlich-1 P. By the time P treatments were applied, this soil contained 4 mg kg^{-1} Mehlich-1 P. By the end of this study, soil Mehlich-1 P concentration in control soils was 3 mg kg^{-1}.

Top Growth Rate

For the Pomona sand in Study 1, St. Augustinegrass top growth responded to P application rates (Table 3). Turf receiving no P produced the lowest amount of top biomass across eight harvests (Table 3). The largest increase on top growth was observed with the first incremental P application (Table 3). For six out of eight harvests, turf with the second lowest P application of 0.14 g m^{-2} 4-wk^{-1} produced the same top growth as higher P application rates (Table 3). The mean value of turf top growth rate with the P application rate of 0.14 g m^{-2} 4-wk^{-1} across eight harvests was 2.7 g m^{-2} d^{-1} and the highest mean value of top growth rate was 3.0 g m^{-2} d^{-1} (Table 3). The top growth for turf with P application rate of 0.14 g m^{-2} 4-wk^{-1} was reduced by 10% from the maximum growth rate. By definition, the amount of nutrient applied that results in 10% reduction in maximum growth is defined as the critical minimum requirement for that nutrient (Moraghan, 1985). Moreover, when the overall means of top growth-rate for each P application rate were compared, turf receiving 0.14 g m^{-2} 4-wk^{-1} produced tissue dry weight that was not significantly different from those receiving higher P application rates by Duncan's multiple range test (Table 3). By either the definition of critical minimum nutrient requirement, or Duncan's multiple range test, the P application rate of 0.14 g m^{-2} 4-wk^{-1} satisfied the minimum P requirement of St. Augustinegrass in Pomona sand.

For the Tavares sand (a) and Pottsburg sand in Study 2, St. Augustinegrass top growth rate varied with P application and soil series (Table 3). Unfertilized soils produced the lowest quantity of top dry-mass across six harvests in both soils (Table 3). The largest increase on top growth rate occurred in the first incremental P application for both soils (1.6 to 2.5 and 1.6 to 2.1 g m^{-2} d^{-1} for soil Tavares sand and Pottsburg sand, respectively) (Table 3). For Tavares sand (a) the top growth for turf receiving 0.14 g m^{-2} 4-wk^{-1} was reduced by approximately 10% from the optimum growth. Moreover, turf receiving 0.14 g m^{-2} 4-wk^{-1} and above achieved equivalent mean top growth rates by Tukey's test. Therefore, a P application rate of 0.14 g m^{-2} 4-wk^{-1} satisfied the minimum P requirement of St. Augustinegrass in Tavares sand (a). However, for Pottsburg sand the top growth rate for turf receiving 0.14 g m^{-2} 4-wk^{-1} was reduced by approximately 30% from the optimum growth rate of 2.8 g m^{-2} d^{-1}. When the 6-harvest means of top growth were subjected to Tukey's test, there were no differences among growth means receiving P application of 0.14 g m^{2} 4-wk^{-1} and above. This was probably due to a larger variation on top growth that occurred when grown in Pottsburg sand. This larger variation may have resulted from more severe disease damage in Pottsburg sand, which particularly influenced growth on turf receiving lower P application rates (0.27 g m^{-2} 4-wk^{-1} and below) (Table 3). These data suggested the benefits of P application on top growth in case of disease incidence.

For the Tavares sand (b) in Study 3, St. Augustinegrass top growth responded to P application (Table 3). Duncan's multiple range test of top growth rate versus P application rate revealed differences in mean top growth rate up to 0.14 g m^{-2} 4-wk^{-1}. Application of additional P beyond 0.14 g m^{-2} 4-wk^{-1} did not increase top growth (Table 3). Relatively smaller growth rate reduction (~25%) was observed in controls in this study compared with those in previous studies. This was due to a higher initial soil

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Table 3. Top growth rate of St. Augustinegrass as influenced by P application rate and soil series.

Soil	P rates	Harvest†								Mean
		1	2	3	4	5	6	7	8	
	g m^{-2} 4 wk^{-1}	g m^{-2} d^{-1}								
	0	2.2b	2.1b	2.1b	1.9b	2.0c	2.1c	2.1b	1.9b	2.1b
	0.14	2.9ab	2.6ab	2.6a	2.3ab	2.4bc	2.5bc	2.9a	2.7a	2.7a
Pomona	0.27	3.0a	2.6ab	2.9a	2.4ab	2.7ab	2.7ab	3.0a	3.0a	2.7a
Sand	0.54	3.0a	2.9a	3.0a	2.5ab	2.9a	3.0ab	3.1a	3.1a	3.0a
	1.09	3.4a	3.0a	3.0a	2.5ab	3.0a	3.1a	3.1a	3.1a	3.0a
CV(%)		18.8	15.4	18.5	16.9	12.7	16.6	8.5	12.9	10.6
	0	2.7a	1.7b	1.6b	1.2b	1.1b	1.7b			1.6b
	0.14	3.5a	2.3ab	2.5a	2.0a	2.4a	2.5ab			2.5a
Tavares	0.27	3.3a	2.4ab	2.9a	2.1a	2.5a	2.8a			2.6a
Sand (a)	0.54	3.8a	2.6a	3.0a	2.3a	2.7a	2.9a			2.9a
	1.09	3.6a	2.7a	3.0a	2.2a	2.8a	3.0a			2.8a
	0	2.5a	1.5b	1.9c	1.3c	1.3b	1.5b			1.6b
	0.14	3.0a	2.0ab	2.1bc	1.6b	2.1ab	2.1ab			2.1ab
Pottsburg	0.27	2.9a	1.7ab	2.2bc	1.6abc	2.1ab	2.2ab			2.1ab
Sand (a)	0.54	3.2a	2.4ab	2.5a	2.1ab	2.5a	2.5ab			2.5a
	1.09	3.4a	2.5a	3.0a	2.2a	2.7a	3.0a			2.8a
CV(%)		18.1	19.7	13.5	15.2	17.6	18			14
	0	3.2b	3.0a	2.8b	1.6c	2.0b	1.5b			2.4b
	0.14	3.8ab	3.1a	3.0ab	1.9ab	2.5ab	1.6ab			2.6a
Tavares	0.27	3.9a	3.1a	3.0ab	2.0a	2.6a	1.7ab			2.7a
Sand (b)	0.54	3.9a	3.3a	3.1ab	2.1a	2.7a	1.7ab			2.8a
	1.09	4.3a	3.4a	3.3a	2.1a	2.7a	1.8a			3.0a
CV(%)		11.3	11.3	10.8	8.8	17.9	13			8

†Within columns for each soil, means followed by the same letter are not significantly different according to Duncan's Multiple Range Test for Pomona sand (Study 1) and Tavares sand (b) (Study 3) and Tukey's Test for Tavares sand (a) and Pottsburg sand (Study 2).

Mehlich-1 P concentration in this soil so that P deficiency on St. Augustinegrass was mildly developed. A coefficient of variation (CV) of less than 10% suggests that there is a small variation among replications.

Tissue P Concentration

For the Pomona sand in Study 1, the initial St. Augustinegrass tissue P concentration tested was as high as 4.9 g kg^{-1} on a dry weight basis. Over time, before P application, tissue P concentration dropped from 4.9 g kg^{-1} to 1.2 g kg^{-1} on dry weight basis. With no P application to turf and very low soil P concentration, it took almost one year to induce P deficiency (<1.6 g kg^{-1} on dry weight basis). Tissue P concentration of St. Augustinegrass as influenced by P application rate in Pomona sand is shown in Table 4. With each incremental P application, tissue P concentration increased across the eight harvests. The highest tissue P level was achieved with application of 1.09 g m^{-2} 4-wk^{-1} and was followed by application of 0.56, 0.27, and 0.14 g m^{-2} 4-wk^{-1} (Table 4). Turfgrass receiving no P maintained a P concentration of 1.0 g kg^{-1}, with which turfgrass showed P deficiency symptoms, reduced turf quality (Table 2), and reduced growth rate (Table 3). In particular, the mean value of tissue P concentration with a P application rate of 0.14 g m^{-2} 4-wk^{-1} was 1.4 g kg^{-1}, which was slightly lower than the critical minimum tissue P concentration (1.6 g kg^{-1}) according to a previous glasshouse hydroponic study (Liu et al., 2006). This indicated that P application of 0.14 g m^{-2} 4-wk^{-1} was almost sufficient to achieve the critical minimum tissue P concentration in this soil. This is consistent with the previous discussion on top growth rate concluding that P application of 0.14 g m^{-2} 4-wk^{-1} satisfied the minimum P requirement of St. Augustinegrass in this soil.

For the Tavares sand (a) and Pottsburg sand in Study 2, the initial tissue P concentration of the St. Augustinegrass was 4.1 g kg^{-1} on a dry-weight basis. Over nine months before P application, tissue P concentration dropped from 4.1 g kg^{-1} to 1.2 g kg^{-1} on dry weight basis. Both soils contained very low Mehlich-1 P (<5 mg kg^{-1}). Tissue P concentration of St. Augustinegrass varied with P rate and soil (Table 4). In both soils, a maximum tissue P level was achieved (3.2 g kg^{-1}) in response to P applied at 1.09 g m^{-2} 4-wk^{-1}. Turfgrass receiving no P maintained a value of 1.0 g kg^{-1}. Tissue P concentration increased with each incremental P application across six harvests for both soils. Maximum top growth was achieved at 0.14 g P m^{-2} 4-wk^{-1} suggesting that application of additional P does not enhance top growth but P uptake (Table 3). Greater tissue P concentrations and top growth were observed in Tavares sand than in Pottsburg sand, indicating a greater P uptake occurred in Tavares sand, possibly caused by a more severe incidence of disease in Pottsburg sand.

For the Tavares sand (b), the initial tissue P concentration of St. Augustinegrass was 5.0 g kg^{-1} on a dry weight basis. Over 15 months before P application, tissue P concentration dropped from 5.0 to 1.3 g kg^{-1} on dry weight basis. The soil Mehlich-1 P decreased from 17 to 4 mg kg^{-1} by the time P was applied. Tissue P concentration of St. Augustinegrass responded to P application (Table 4). Tissue P concentra-

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tion increased with each incremental P application across six harvests. A maximum tissue P level (3.4 g kg^{-1}) was achieved in response to phosphorus applied at 1.09 g m^{-2} 4-wk^{-1}. Turfgrass receiving no P maintained a value of 1.4 g kg^{-1}, which was higher than those found in the previous Studies 1 and 2 (1.0 g kg^{-1}). This explains the smaller top-growth rate reduction in controls and only mild P deficiency symptoms observed in this study. The soil used in this study supplied a substantial quantity of P for St. Augustinegrass growth over the entire experiment period.

Table 4. Tissue P concentration of St. Augustinegrass as influenced by P application rate and soil series.

Soil	P rates	Harvest† 1	2	3	4	5	6	7	8	Mean
	g m^{-2} 4-wk^{-1}	g m^{-2} d^{-1}								
	0	1.1d	1.1d	1.1d	1.0d	1.0d	1.0d	0.8d	1.0e	1.0e
	0.14	1.5cd	1.5cd	1.5c	1.4c	1.5c	1.3cd	1.3d	1.5d	1.4d
Pomona	0.27	1.7c	1.6c	1.7c	1.7c	1.7c	1.8c	1.8c	2.1c	1.8c
Sand	0.54	2.5b	2.3b	2.6b	2.3b	2.4b	2.4b	2.7b	3.0b	2.5b
	1.09	3.5a	3.2a	3.3a	3.1a	3.5a	3.3a	3.4a	4.1a	3.4a
CV(%)		17.7	18.8	15.3	15.1	15.3	19.5	17.5	8.1	11.2
	0	1.1d	0.98c	0.94c	0.94c	1.1d	0.89c			0.98d
	0.14	1.3cd	1.2c	1.2c	1.3c	1.4cd	1.3c			1.3cd
Tavares	0.27	1.5c	1.4bc	1.4c	1.4abc	1.9c	1.6bc			1.5c
Sand (a)	0.54	2.0b	1.8b	2.3b	2.2ab	2.9b	2.1b			2.2b
	1.09	3.1a	2.7c	3.1a	3.0a	3.8a	3.3a			3.2a
	0	1.1d	0.93c	1.0c	1.0c	1.0d	1.0c			1.0c
	0.14	1.2c	1.0c	1.1c	1.0c	1.4cd	1.2c			1.2c
Pottsburg	0.27	1.5c	1.2bc	1.2bc	1.3bc	1.9c	1.5c			1.4c
Sand (a)	0.54	2.0b	1.7b	1.8b	1.9b	2.6b	2.2b			2.0b
	1.09	3.3a	2.6a	2.5a	2.8a	3.9a	3.5a			3.2a
CV(%)		10.8	15.6	17.7	24.5	11.8	17.7			10.3
	0	1.3d	1.4b	1.3d	1.2d	1.5d	1.5e			1.4d
	0.14	1.4d	1.5b	1.7cd	1.5c	1.8d	1.9d			1.6d
Tavares	0.27	1.8c	2.1a	1.9bc	1.7c	2.3c	2.5c			2.0c
Sand (b)	0.54	2.2b	2.3a	2.3b	2.4b	3.0b	3.5b			2.6b
	1.09	2.9a	2.4a	3.4a	3.3a	4.1a	4.6a			3.4a
CV(%)		15	20	14.3	8.8	14.1	9.4			8.6

†Within columns for each soil, means followed by the same letter are not significantly different according to Duncan's Multiple Range Test for Pomona sand (Study 1) and Tavares sand (b) (Study 3) and Tukey's Test for Tavares sand (a) and Pottsburg sand (Study 3).

The Critical Minimum Tissue P Concentration

For the Pomona sand in Study 1, tissue growth rate was increased with tissue P concentration in a quadratic manner to a maximum value (Fig. 1). The slope of the regression curve can be defined as the change of tissue growth rate over the change of tissue P concentration. The nearly vertical portion of the regression curve shows relatively steeper slopes and the horizontal portion has a slope of zero. The transition zone is the area of the curve where the vertical and horizontal portions converge. With the increase of the tissue P concentration the slope gradually decreases until it reaches zero, which is the plateau of the curve. According to linear plateau regression analysis, the critical tissue P level was 1.8 g kg^{-1} on dry weight basis for the optimum growth (R^2 = 0.77, P < 0.0001, CV = 10.9%).

For the Tavares sand (a) and Pottsburg sand in Study 2, the critical minimum tissue P concentration was 1.9 g kg^{-1} (Fig. 1), according to nonlinear plateau regression analysis (R^2 = 0.70, P < 0.0001, CV = 12.2%). The maximum top growth estimated in the quadratic relationship was 2.8 g kg^{-1}, which was the same as the optimum growth corresponding to the highest P application rate of 1.09 g m^{-2} 4-wk^{-1}, suggesting a reasonable plateau. In a previous solution culture study, the critical tissue P concentration was determined to be 1.6 g kg^{-1} (Liu et al., 2006. The small discrepancy between the previous hydroponic study and this soil study could be simply due to experiment error or physiological difference between growth in nutrient solution and soil.

For the Tavares sand (b) in Study 3, the critical minimum tissue P concentration was determined to be 1.8 g kg^{-1} (Fig. 1), according to nonlinear plateau regression analysis (R^2 = 0.48, P < 0.001, CV = 8.6%). The coefficient of determination was lower than that found in previous soil Studies 1 and 2. This was possibly caused by three or four data points falling beyond average. The maximum top growth rate estimated in the quadratic relationship was 2.9 g kg^{-1}, which was consistent with the optimum growth rates (2.9 and 2.8 g kg^{-1} for soil Studies 1 and 2, respectively), suggesting a reasonable plateau.

The Critical Minimum Soil Test P Concentration

For the Pomona sand in Study 1, application of the various P rates up to 1.09 g m^{-2} 4-wk^{-1} resulted in a range of extractable soil Mehlich-1 P concentration (0.5 to 16.7 mg kg^{-1}). Growth of St. Augustinegrass was affected by soil Mehlich-1 P concentrations (Fig. 2). Responses were described relatively well by the quadratic response and plateau model with the coefficients of determination being 0.71 and P values of less than 0.0001. The critical

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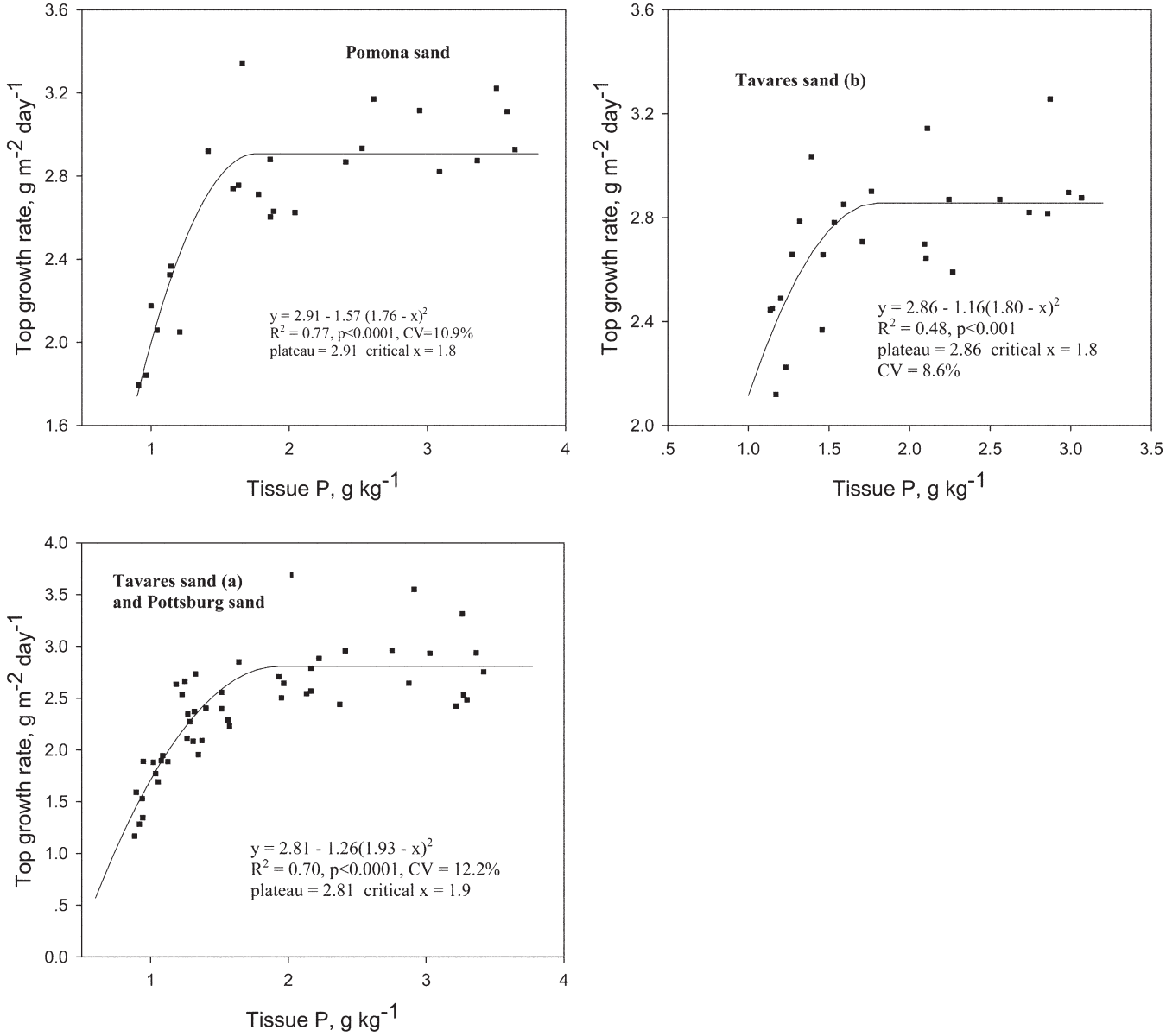

Figure 1. St. Augustinegrass tissue growth rate relative to tissue P concentration in four soil series.

concentration of the soil Mehlich-1 P was determined to be 7 mg kg^{-1}.

For the Tavares sand (a) and Pottsburg sand in Study 2, the growth of St. Augustinegrass was affected by soil Mehlich-1 P concentration (Fig. 2). Application of phosphorus up to 1.09 g m^{-2} 4-wk^{-1} resulted in a range of Mehlich-1 P concentrations from 0.2 to 10.5 and 0.6 to 9.5 mg kg^{-1} for Tavares sand and Pottsburg sand, respectively. Growth rate vs. Mehlich-1 P in both soils was described by the quadratic response and plateau model with the coefficients of determination being 0.54 and 0.60 for Mehlich-1 in Tavares sand and Pottsburg sand, respectively. The critical Mehlich-1 P concentration obtained for Tavares sand and Pottsburg sand were 8 and 9 mg kg^{-1}, respectively. For the Tavares sand (b) in Study 3, growth rate vs. Mehlich-1 P was described by the quadratic response and plateau model with the coefficients of determination of 0.27 and *P* value less than 0.05. The critical Mehlich-1 P concentration obtained was 5 mg kg^{-1}, which was somewhat lower than the critical Mehlich-1 P concentrations of 7, 8, and 9 mg kg^{-1} determined for Pomona sand, Tavares sand (a), and Pottsburg sand, respectively. This was expected because this soil contained a larger quantity of Al and Fe oxides and has a larger P buffering capacity. For each unit of soil test P level decrease, Tavares sand (b) supplied a larger quantity of P for plant uptake.

In the state of Florida, Mehlich-1 soil P below 16 mg kg^{-1} is categorized as low P, and below 10 mg kg^{-1} as very low P. Phosphorus fertilization would be recommended in those cases. These data suggest that optimum growth of St. Augustinegrass can be attained at very low Mehlich-1 soil test P levels. Phosphorus application is recommended for medium levels of soil Mehlich-1 P according to current interpretation criteria. Therefore, the P recommendations based on P status categories would lead to over-fertilization

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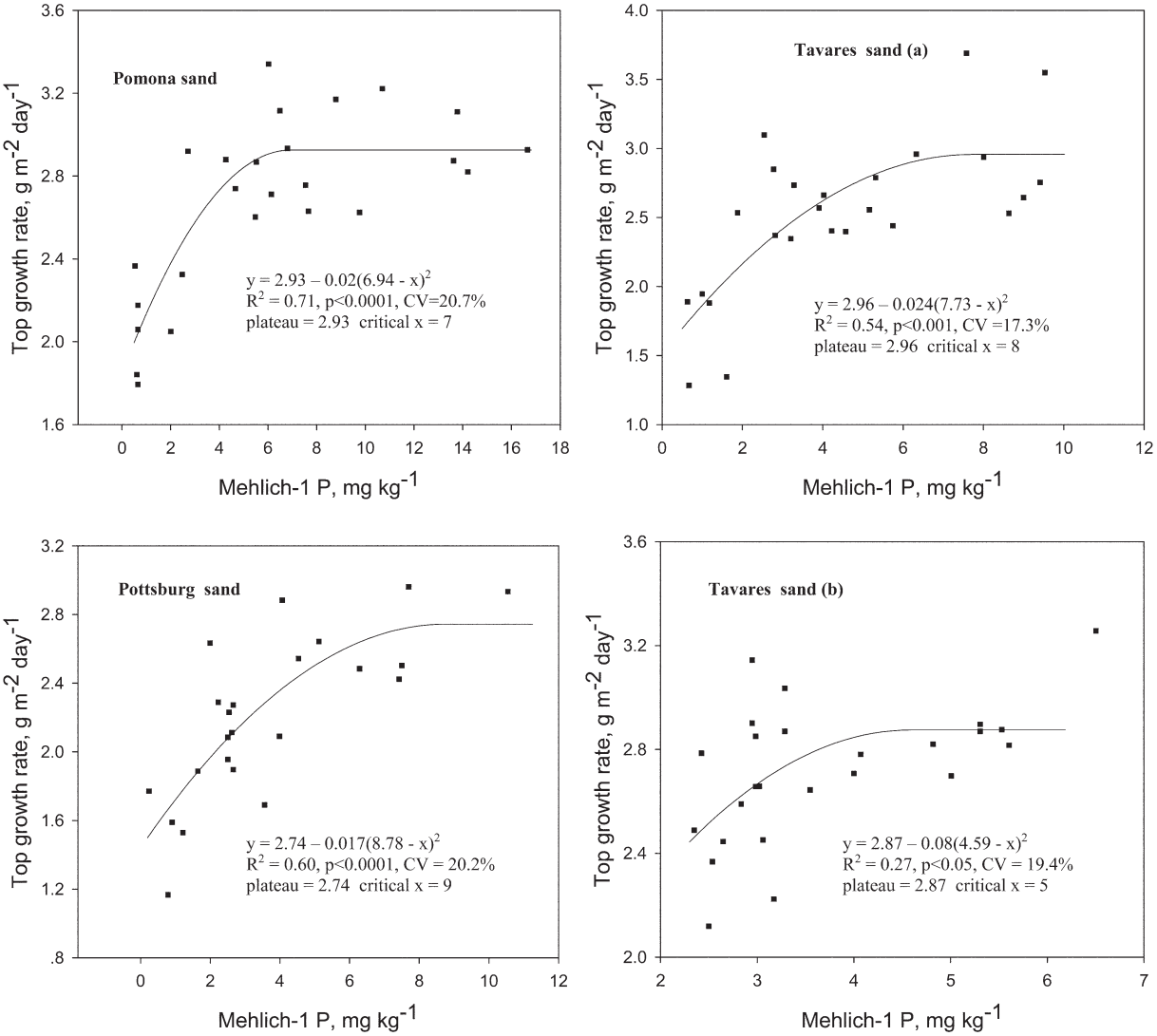

Figure 2. St. Augustinegrass tissue growth rate relative to soil Mehlich-1 P concentration in four soil series.

of P on St. Augustinegrass. The P status categories specifically for St. Augustinegrass need to be adjusted according to these findings. No P application would be recommended if Mehlich-1 P concentration is above 10 mg kg^{-1}.

CONCLUSIONS

Phosphorus application of 0.14 g m^{-2} 4-wk^{-1} achieved the best turf quality in three out of four soils. Moreover, P application above 0.14 g m^{-2} 4-wk^{-1} did not result in additional top growth. Therefore, the minimum P application rate was approximately 0.14 g m^{-2} 4-wk^{-1} for these four sandy soils. A previous hydroponic study indicated that St. Augustinegrass can be expected to respond favorably to P applications if the tissue P concentrations were less than 1.6 g kg^{-1} (Liu et al., 2006). These studies showed that in these four soils the critical minimum tissue P concentration was 1.8 g kg^{-1}. The small discrepancy could be the result of experiment error or physiological differences between growth in nutrient solution and soil. Phosphorus fertilization would not result in a growth response beyond 7, 8, 9, and 5 mg kg^{-1} for Mehlich-1 P in Pomona sand, Tavares sand (a), Pottsburg sand, and Tavares sand (b), respectively. On the basis of the findings of this study no P fertilization would be recommended if soil Mehlich-1 P concentration is above 10 mg kg^{-1} or tissue P level is beyond 1.8 g kg^{-1} on dry weight basis. Phosphorus application of 0.14 g m^{-2} 4 wk^{-1} is recommended if needed. One criticism of the Mehlich-1 procedure is that it extracts an insoluble portion of P in soil which might not be available to plants. Future studies may include selecting the most suitable soil-testing procedure for St. Augustinegrass by comparing different P extractants. This study was informative under a controlled glasshouse environment; future studies should be conducted to confirm these findings in the field.

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