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Orthophosphate Leaching in St. Augustinegrass and Zoysiagrass Grown in Sandy Soil under Field Conditions

Ronald F. Gonzalez,* Jerry B. Sartain, Jason K. Kruse, Thomas A. Obreza, George A. O'Connor, and Willie G. Harris

Phosphorus (P) is required to maintain healthy, high-quality, warm-season turf. However, excessive P applications to soils with poor P retention capabilities may lead to leaching losses to groundwater. This field study was conducted to determine the maximum P fertilizer application rate to *Stenotaphrum secundatum* (Walt.) [Kuntze] 'Floratam' St. Augustinegrass (St. Augustinegrass) and *Zoysia japonica* 'Empire' zoysiagrass (zoysiagrass) below which P leaching is minimized. Five P levels ranging from 0 to 5.0 g P m^{-2} yr^{-1} were surface applied as triple superphosphate. Turf was established on an uncoated, low-P sand with negligible P retention capacity. Leaf and root growth, tissue P concentration, soil P concentration, soil P saturation, leachate volume, and orthophosphate (P_i) concentration in leachates were measured. Mehlich 1–extractable soil P (M1-P) and soil P saturation ratio (PSR) increased with time as the P rate increased. Lower M1-P and PSR values were measured with St. Augustinegrass, which absorbed more P than did zoysiagrass. The root system of St. Augustinegrass was larger and deeper compared with zoysiagrass, promoting greater P uptake and less P leaching. If tissue analysis indicates that P fertilization is required and the soil has the capacity to retain additional P, application of 0.8 g P m^{-2} yr^{-1} to zoysiagrass and 1.07 g P m^{-2} yr^{-1} to St. Augustinegrass is appropriate and does not result in increased P_i leaching.

Phosphorus leaching to groundwater from turfgrass landscapes may increase the P concentration of surface water bodies. Eutrophication of P-limited aquatic systems has been linked to enrichment of the water column with P (Correll, 1998; Carpenter et al., 1998; Foy, 2005). The risk of P leaching is greater in soils dominated by "clean" (uncoated) sands compared with soils containing coated sands (Harris et al., 1996). Sand coatings impart soil P retention capacity because constituents like kaolinite, hydroxyl-interlayered vermiculite, and metal oxides have greater affinity for P than uncoated quartz surfaces. In acid sandy soils with low organic matter content, P retention is largely controlled by Al- and Fe-bearing soil components (Sims et al., 1998; Sims et al., 2002).

Continuous P fertilization over time can increase the soil P concentration and the risk of soil P loss to the environment. Phosphorus concentration in leachates and runoff has been reported to increase with increasing soil test P (STP) (Heckrath et al., 1995; Pote et al., 1999; Maguire and Sims, 2002b). Soil test P by itself may not provide sufficient information to assess the risk of P losses from the soil to water bodies (Pautler and Sims, 2000; Hooda et al., 2000). Soils with low STP levels may not be able to retain additional P, whereas soils with high STP values may have the capacity to retain added P (Nair and Harris, 2004).

The ability of the soil to retain P can be evaluated through indices that account for the P concentration in the soil and the capacity of the soil to retain additional P (Pautler and Sims, 2000; Hooda et al., 2000). One of these indices is the degree of soil P saturation (DPS), defined as the molar ratio of P to the sum of aluminum (Al) and iron (Fe) extracted in acid ammonium oxalate solution (van der Zee et al., 1987; Breeuwsma and Silva, 1992). The DPS is expressed as a percentage and includes the empirical parameter α in its calculation (DPS = $[P/\alpha\,(Al + Fe)] \times 100$) to account for the fraction of Al and Fe responsible for P sorption for a given soil (van der Zee et al., 1987; Breeuwsma and Silva, 1992).

R.F. Gonzalez, J.B. Sartain, G.A. O'Connor, T.A. Obreza and W.G. Harris, Soil and Water Science Dep., Univ. of Florida, P.O. Box 110290, Gainesville, FL 32611; J.K. Kruse, Environmental Horticulture Dep., Univ. of Florida, P.O. Box 110670, Gainesville, FL32611. Assigned to Associate Editor Goswin Heckrath.

Abbreviations: DM, dry matter; DPS, degree of soil phosphorus saturation; HDPE, high-density polyethylene; M1-Al, Mehlich 1–extractable soil aluminum; M1-Fe, Mehlich 1–extractable soil iron; M1-P, Mehlich 1–extractable soil P; P_i, orthophosphate (dissolved inorganic phosphorus); PSR, soil phosphorus saturation ratio; RD, root diameter; RLD, root length density; RSA, root surface area; RV, root volume.

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*Corresponding author (rfgonzalezdr@gmail.com).

The risk of soil P loss through leaching has also been assessed with the soil P saturation ratio (PSR). The PSR is the molar ratio of Mehlich 1– or Mehlich 3–extractable P to extractable [Al + Fe] (Sims et al., 2002). Plots of P concentration in leachate against PSR showed distinct PSR "change points" above which an abrupt increase in leachate P concentration was observed (Sims et al., 2002; Maguire and Sims, 2002a; Maguire and Sims, 2002b). In a study conducted with Florida sandy soils by Nair et al. (2004), water-extractable P concentration increased rapidly above a PSR (calculated with Mehlich 1–extractable soil P, Al, and Fe) of 0.10 (95% confidence interval, 0.05–0.15), and $CaCl_2$–extractable soil P concentration increased abruptly above a PSR of 0.19 (95% confidence interval, 0.15–0.23). Nair et al. (2004) proposed a threshold PSR of 0.15 to reduce the risk of P loss to the environment through runoff and subsurface drainage from sandy soils in Florida.

Excessive P fertilization of turfgrass grown in sandy soils with low P retention capacities and abundant macropores promotes P leaching (Soldat and Petrovic, 2008). Guertal (2007) reported that P leaching from 'Tifdwarf' hybrid bermudagrass (*Cynodon* spp.) established on a sand-based putting green increased as the rate of P applied increased. In Florida, the "Labeling Requirements for Urban Turf Fertilizers rule" (Rule 5E-1.003) limits the amount of P per application to 0.53 g m^{-2} or 1.07 g m^{-2} yr^{-1} (State of Florida, 2007).

Excessive home lawn irrigation can increase nutrient leaching (Snyder et al., 1984; Morton et al., 1988). The growth characteristics of different plant species can also influence nutrient leaching. In a south Florida study, greater P leaching occurred from a mix of ornamentals, woody shrubs, and trees than from a 'Floratam' St. Augustinegrass [*Stenotaphrum secundatum* (Walt) Kuntze] monoculture (Erickson et al., 2005). However, no studies of the differences in P leaching among home lawn warm-season turfgrasses were found.

In Florida, 'Floratam' St. Augustinegrass (St. Augustinegrass) is the most widely used turfgrass, and *Zoysia japonica* 'Empire' zoysiagrass (zoysiagrass) occupies the fourth largest area of sod production in the state (Satterthwaite et al., 2009). In 2007, Florida had more than 1.2 million ha in managed home lawns, and more than $3.2 billion was spent on associated goods and services (Hodges and Stevens, 2010).

Phosphorus leaching from turfgrass is influenced by a wide variety of factors and their complex interactions. Improved understanding of the relationship between P application rate and P leaching from St. Augustinegrass and zoysiagrass under highly favorable conditions for P leaching is needed. The objectives of this experiment were (i) to evaluate the relationship between P fertilizer rate and dissolved inorganic P (P_i) leaching rate for zoysiagrass and St. Augustinegrass and (ii) to study the interaction between plant P uptake, rainfall, irrigation, and soil PSR with P_i leaching rate in these turfgrass systems.

Materials and Methods

Experimental Site and Treatments Description

The study was conducted during the 2008 and 2009 growing seasons (May–September) at the G.C. Horn Turfgrass Laboratory, Plant Science Research and Education Unit of the University of Florida near Citra, Florida (29°24′ N; 82°10′ W). Climatic conditions were: mean temperature at 60 cm above the turf surface, 26°C (range, 13.7–38.6°C), cumulative precipitation (not including irrigation) of 383 mm in 2008 and 723 mm in 2009, and cumulative evapotranspiration of 462 mm in 2008 and 540 mm in 2009. Cumulative precipitation from October to April was 519 mm in 2008 and 367 mm in 2009, and cumulative evapotranspiration was 506 mm in 2008 and 510 mm in 2009.

Forty plots (3 m by 4.25 m) were established. A rectangular area (1.5 m by 4.25 m) of native soil was excavated in the center of each plot to a depth of 45 cm. An additional amount of soil was excavated to place high-density polyethylene (HDPE) lysimeters in the center of the excavated area. The lysimeter and excavated area were filled with low-P sand (<10 mg kg^{-1} of M1- P and <1% clay size fraction with traces of kaolinite and gibbsite). The low-P sand was extracted from a mine pit and was selected due to its low P retention capacity to create highly favorable conditions for P leaching. The lysimeters were 55 cm in diameter and 70 cm in height with a conical base (~166 L). Lysimeters were placed on a galvanized steel base that was 25.4 cm in height. The bottom of each lysimeter was filled to a depth of 15 cm with washed gravel, which served as a leachate reservoir. The gravel was covered with a nonwoven polyolefin cloth secured with a hoop of HDPE tubing (13 mm inner diameter) to reduce soil intrusion into the leachate collection basin. Low-density polyethylene tubing (9.5 mm outer diameter and 6.35 mm inner diameter) was connected to the base of each lysimeter and run underground to the aboveground leachate collection towers. Each tube was number coded and attached to the corresponding outlet in a box placed on the leachate collection tower. Once in place, the lysimeter and the excavated area were filled with low-P sand. After back-filling the excavated area, the top of the lysimeter was approximately 10 cm below the soil surface.

Turfgrasses were established with soil-free certified sod from the G.C. Horn Turfgrass Field Laboratory of the University of Florida. The experiment was set up in a split-plot, randomized, complete block design with turfgrass species as the main plot and P application rate as the subplot. The test cultivars were *S. secundatum* (Walt) Kuntze 'Floratam' and *Z. japonica* 'Empire'. Four P fertilizer applications were conducted during the first growing season (2008) at 0, 0.08, 0.2, 0.5, and 1.25 g P m^{-2} every 4 wk. Two P fertilizer applications were performed during the second year (2009) at 0, 0.04, 0.1, 0.25, and 0.625 g P m^{-2} every 8 wk. Phosphorus application rates were replicated four times.

The source of P fertilizer was concentrated superphosphate (45% P_2O_5), which was uniformly broadcast over the turf surface. In addition to P, all plots were fertilized with 4.9 g m^{-2} of nitrogen (N) and 4.06 g m^{-2} of potassium (K) in combination with the P fertilizer (Trenholm and Unruh, 2005; Sartain, 2010). At the beginning of the 2009 growing season, all plots were verticut to reduce thatch buildup. All plots were irrigated with approximately 10 mm of water five times per week during the evaluation period (~18 wk per growing season). Irrigation was conducted regardless of rainfall. In Florida, two or three irrigations of 12.7 to 19 mm per week are recommended for home lawns during summer days without rainfall. Once rainfall has resumed, no irrigation is recommended until the turf exhibits signs of drought (Trenholm and Unruh, 2005).

Soil and Plant Tissue Sampling and Analysis

Soil and tissue samplings started about 1 yr after sodding. Soil samples were collected before treatment application and every 2 wk thereafter for the duration of each growing season. Composite samples consisting of two soil cores from depths of 0 to 7.5 cm, 7.5 to 15 cm, and 15 to 30 cm per plot were collected with a 2-cm-diameter stainless steel soil probe. The holes created while sampling were refilled with low-P sand immediately after collecting the sample. Soil samples were air dried and passed through a 2-mm sieve. Soils were analyzed for Mehlich 1 (1:4 soil to 0.125 mol L^{-1} H_2SO_4 + 0.05 mol L^{-1} HCl solution, 5-min reaction time, and filtration through Whatman no. 42 filter paper)–extractable soil P, iron (M1-Fe), and aluminum (M1-Al) (Mehlich, 1953). Mehlich 1–extractable soil iron and Al concentrations were measured using atomic absorption spectrophotometry (Varian Inc.). Soil carbon (C) and nitrogen (N) contents were measured with a Thermo Electron Flash (EA1112) N and C Analyzer (Thermo Electron Corp.). Soil pH and electrical conductivity were determined in 2:1 (v/v) water:soil ratio after a 30-min equilibration period.

Soil P saturation ratio (PSR) was calculated according to the following equation:

$$\text{PSR} = \text{M1-P}/(\text{M1-Fe} + \text{M1-Al}) \qquad [1]$$

where M1-P, M1-Fe, and M1-Al are expressed in moles (Nair et al., 2004).

The relative soil P adsorption capacity was determined according to the procedure described by Harris et al. (1996) and was calculated as the ratio of total P adsorbed and maximum possible P that could be adsorbed from a solution representing a P load of 400 mg kg^{-1} soil.

Tissue samples were collected immediately before the first P fertilization and biweekly after treatment application for the duration of the growing season. Samples were collected by harvesting the leaf tissue from the low-P sand area along the length of the plots. Clippings were collected with a walk-behind mower with a bag collector. The width of the mower swath was 54 cm, and the turf area harvested per plot was 1.29 m^2. The mowing height was approximately 10.2 cm for St. Augustinegrass and 7.62 cm for zoysiagrass.

At the end of the 2008 growing season, root samples consisting of two 383-cm^3 soil cores per plot were taken from the top 15 cm of the soil profile for each treatment. During 2009, root samples were collected before imposing P treatments at the beginning of the season and every 4 wk thereafter. The root sampling depths during 2009 were 0 to 15 cm and 15 to 30 cm. All root samples were washed free of soil and scanned with an Epson Perfection V700 Photo dual lens scanner (Epson Corp.). The digital images obtained were analyzed with WinRhizo Software Pro v. 2007d (Reagent Instruments Canada, Inc.) to determine the root length density (RLD), root surface area (RSA), root volume (RV), and average root diameter (RD). Thatch tissue was separated from roots and washed free of soil. Leaf, thatch, and root samples were oven dried at 70°C to constant weight, and dry matter (DM) content was recorded. Tissue samples were ground to pass a #40 mesh sieve (425-μm openings size). Dry tissue was ashed and digested following the procedure of Andersen (1976). Phosphorus concentrations in the digestate of plant tissues and the soil sample extracts were determined by colorimetry following the procedure described by O'Dell (1993).

Leachate Collection, Sampling, and Analysis

Leachate samples were collected before treatment application (i.e., baseline sampling) and every 7 d thereafter during each growing season. Leachates were sampled according to a protocol approved by the Florida Department of Environmental Protection. Leachates were collected from the lysimeter by creating a vacuum (~0.85 bars of tension) in the leachate collection line with a vacuum pump. The entire volume of leachates was collected in 20-L HDPE containers, and the leachate volume was determined by weight. Leachate samples were collected into 30-mL polyethylene syringes beginning 1 min after continuous leachate flow had started. Leachate samples were passed through disposable 0.45-μm pore size filters, and the filtrate was dispensed into 20-mL scintillation vials. Immediately after collection, each sample was placed in a cooler with ice water and kept between 0 and 4°C (no acid added). Upon arrival at the laboratory, samples were checked to make sure they were within the required temperature range. The concentration of P_i in leachate samples was determined within 24 h after sampling, and all analytical results were certified by the quality assurance/quality control officer of the Wetland Biogeochemistry Laboratory of the University of Florida. Phosphorus concentration in the leachates was determined by colorimetry (practical quantitation limit, 0.01 mg P L^{-1}) following the procedure described by O'Dell (1993).

The cumulative amount of P_i leached in excess of that measured in the control treatment was used to estimate the P leached from applied fertilizer. No fertilizer P was applied during 2010; however, the P_i leached until June 2010 was taken into account to estimate the amount of P leached from fertilizer application during the entire evaluation period (May 2008 to June 2010).

Statistical Data Analysis

Normal distribution of the data was tested graphically using normal probability plots and numerically with the Shapiro-Wilk W test. Equal variance was checked using residual plots and the Levene's test for homogeneity of variance. Natural Log transformation of P_i leaching rate and P_i concentration in leachate was required to meet ANOVA assumptions. Due to significant interactions between turfgrass species, years, and treatments, the data were analyzed separately for each species within each year. Analysis of variance was conducted with the general linear model procedure (Proc GLM) of SAS system v.9.2 (SAS Institute, 2009), and mean separation was performed with single degree of freedom contrast analysis.

Results

Influence of Applied Phosphorus on Selected Soil Chemical Properties

Soil M1-P concentration in the top 15 cm before P application was <3.5 mg kg^{-1}, and total soil C content was low (Table 1). Silt plus clay-sized particles accounted for <2% by mass, and most of the top soil was composed of medium and fine sand–size particles (0.10–0.50 mm diam.) (Table 1). X-ray diffraction analysis of the clay-sized fraction of the sand used in this study revealed the presence of only traces of kaolinite and gibbsite. Before imposing the P treatments, the sand used in this study as the growth medium had negligible relative soil P adsorption capacity, and the average PSR was 0.33 (Table 1). Soil pH in the top 15 cm of the profile before treatment was 6 (Table 1).

There was no statistically significant treatment effect on M1-P and PSR for either turfgrass species during the first growing season, but M1-P and PSR tended to increase with increasing P supply (Table 2). During 2009, M1-P and PSR increased for both species with increasing P rate (Table 2). Average PSR across treatments in zoysiagrass was 38.5% greater in 2008 and 26.8% greater in 2009 than in St. Augustinegrass (Table 2). In 2008, M1-P values in soil under zoysiagrass were greater than in soil under St. Augustinegrass (Table 3). In 2009, M1-P at the 0- to 15-cm depth did not differ significantly between species; however, it was greater for zoysiagrass at the 15- to 30-cm depth (Table 3). Mehlich 1–extractable soil P increased significantly from 2008 to 2009 in both species (Table 3).

Phosphorus Uptake and Shoot and Root Growth Parameters

Leaf tissue P concentrations were greater than the critical leaf P concentrations required for maximum growth rate identified for zoysiagrass (1.67 g P kg^{-1}) (Gonzalez, 2010) and St. Augustinegrass (1.8 g P kg^{-1} DM) (Liu et al., 2008). Phosphorus concentrations in leaf tissue across P fertilizer treatments were greater in St. Augustinegrass than in zoysiagrass in both growing seasons (Table 3). Leaf growth rates and P uptake rates were also greater in St. Augustinegrass than in zoysiagrass during both years (Table 3). There was no significant P fertilizer treatment effect on plant P uptake rate for either turfgrass species in either evaluation year (data not shown). St. Augustinegrass P uptake rate decreased from 2008 to 2009. Zoysiagrass P uptake rate did not change significantly between 2008 and 2009 (*P* = 0.492). On average across treatments and evaluation years, the amount of thatch DM accumulated per square meter was 435 g greater for zoysiagrass than for St. Augustinegrass.

During the first growing season after P application (2008), root DM and RSA did not differ between species. However, root volume and average root diameter were greater in St. Augustinegrass than in zoysiagrass (Table 3). During the 2009 growing season, root DM, RSA, RV, and RD of root samples of St. Augustinegrass collected from the top 15 cm of the soil profile were greater than for zoysiagrass, and RV showed the greatest difference (Table 3). A similar trend was observed in root samples collected from the 15- to 30-cm depth (Table 3). Root systems differed in architecture between species. During the 2009 growing season, an average of 35% of the total root biomass, 40% of the RLD, 38% of the RSA, and 37% of the RV of St. Augustinegrass contained in the top 30 cm of the soil profile were located in the 15- to 30-cm portion (Table 3). In the case of zoysiagrass during the same year, on average only 19% of the total root DM, 31% of the RLD, 24% of the RSA, and 18% of the RV from the top 30 cm of the soil profile were contained in the 15- to 30-cm soil layer (Table 3). Root DM, RLD, RSA, and RV values from the top 15 cm of the soil profile were less at the beginning and at the end of the 2009 growing season than near midseason for both grasses (data not shown).

Table 1. Baseline (May 2008) surface low-phosphorus refill sand (0–15 cm) characterization planted with 'Empire' zoysiagrass and 'Floratam' St. Augustinegrass grown in the field near Citra, FL (*n* = 20).

Variable	Units	Value
Mehlich 1–extractable P (M1-P)	mg kg^{-1}	3.47
Mehlich 1–extractable Al (M1-Al)	mg kg^{-1}	11.0
Mehlich 1–extractable Fe (M1-Fe)	mg kg^{-1}	1.46
Total C	g kg^{-1}	0.40
Total N	g kg^{-1}	0.10
pH		6.0
Soil electrical conductivity	µS cm^{-1}	28.3
Relative P adsorption capacity†		0.01
Phosphorus saturation ratio‡		0.33
Slope	%	0
Silt + clay	%	<2
Particle size, mm		
Very fine (0.05–0.1)	%	0.9
Fine (0.1–0.25)		30
Medium (0.25–0.5)		46.2
Coarse (0.5–1.0)		20.4
Very coarse (1.0–2.0)		2.5

† Calculated as the amount of P adsorbed/maximum possible P adsorption. Under the experimental conditions used in this study, the maximum possible P adsorption was 400 mg P kg^{-1} (Harris et al., 1996).

‡ Calculated as M1-P/(M1-Fe + M1-Al), where M1-P, M1-Fe, and M1-Al are expressed in moles (Nair et al., 2004).

Table 2. Effect of phosphorus application rate during the 2008 and 2009 growing seasons on Mehlich 1–extractable soil phosphorus and soil phosphorus saturation ratio in the top 15 cm of the soil profile under 'Empire' zoysiagrass and 'Floratam' St. Augustinegrass grown in the field on a low-phosphorus sand near Citra, Florida.

P fertilizer application†	Empire zoysiagrass		Floratam St. Augustinegrass	
	M1-Pǂ	PSR§	M1-P	PSR
	mg P kg^{-1}		mg P kg^{-1}	
		2008		
0 g P m^{-2}	2.52	0.38	2.27	0.38
0.08 g P m^{-2}	2.92	0.46	1.61	0.27
0.2 g P m^{-2}	3.15	0.51	1.90	0.28
0.5 g P m^{-2}	3.55	0.57	2.70	0.44
1.25 g P m^{-2}	3.40	0.56	2.91	0.42
P value	0.4037	0.2393	0.1784	0.0526
		2009		
0 g P m^{-2}	3.79c¶	0.62c	4.56b	0.75b
0.04 g P m^{-2}	5.76b	0.92b	5.00b	0.76b
0.1 g P m^{-2}	6.54b	1.05b	5.48b	0.76b
0.25 g P m^{-2}	9.66a	1.31a	5.84b	0.92b
0.625 g P m^{-2}	9.53a	1.50a	9.75a	1.07a
P value	<0.0001	<0.0001	<0.0001	<0.0001

† Phosphorus fertilizer was applied every 4 wk (four applications) during 2008 and every 8 wk (two applications) during 2009. The source of P was concentrated superphosphate (45% P_2O_5).

ǂ Mehlich 1–extractable soil phosphorus.

§ Phosphorus saturation ratio. PSR = M1-P/(M1-Fe + M1-Al), where M1-P, M1-Fe, and M1-Al are expressed in moles (Nair et al., 2004).

¶ Values within a given year and column with the same letter are not statistically different at *P* = 0.05 according to single degree of freedom contrast analysis.

Orthophosphate Leaching Rate

Leachate volume per lysimeter across turfgrass species and growing seasons ranged from 1.9 to 28.4 L (average, 10.4 L m^{-2} d^{-1}). Orthophosphate leaching from zoysiagrass and St. Augustinegrass control treatments (Fig. 1) was observed in both years. The rate of P_i leaching from unfertilized St. Augustinegrass was 5.5- and 2-fold lower compared with the zoysiagrass control treatment during 2008 and 2009, respectively (Fig. 1). Average P_i leaching rate (mg P_i m^{-2} d^{-1}) across P-fertilized treatments for zoysiagrass was 11-fold greater during the 2008 growing season and 6-fold greater during 2009 growing season than for St. Augustinegrass (Fig. 1).

During the 2008 growing season, application of 0.8 g P m^{-2} yr^{-1} (i.e., 0.2 g P m^{-2} every 4 wk) to zoysiagrass did not increase the rate of P_i leaching relative to the control (Fig. 1). The rate of P_i leaching from St. Augustinegrass during 2008 was not different between the fertilized treatments and the control (Fig. 1).

Mean P_i leaching rate across treatments applied to zoysiagrass decreased by 31% from 2008 to 2009 (Fig. 1). During 2009, P rates of 0.1 g m^{-2} per application (0.2 g m^{-2} yr^{-1}) to zoysiagrass and 0.25 g m^{-2} per application (0.5 g m^{-2} yr^{-1}) to St. Augustinegrass (Fig. 1) did not increase P_i leaching over that of the control.

Changes in the P_i leaching rate with time were associated with fluctuations in the sum of rainfall plus irrigation (total water input) that the turf received (Fig. 2). Fluctuations in the total water received by the turf explained a total of 73% of the variability in leaching rate from zoysiagrass and 50% of the variability in leaching rate from St. Augustinegrass. Total water input in 2009 was about 45% greater than in 2008. Leachate volume across years and treatments increased linearly with increasing total water input for zoysiagrass ($y = 0.16x + 4.28$; $r^2 = 0.64$; CV = 25%; $p < 0.0001$) and St. Augustinegrass plots ($y = 0.17x + 3.98$; $r^2 = 0.63$; CV = 27%; $p < 0.0001$).

About 0.41% of the highest P level applied to St. Augustinegrass was leached (Table 4). The maximum amount of P leached from St. Augustinegrass between May 2008 and June 2010 was 0.026 g m^{-2}, which corresponded to a P application of 6.25 g m^{-2} between May 2008 and June 2010 (Table 4). For zoysiagrass, about 9% of the applied P, a total of 0.558 g P m^{-2}, was leached from the highest P treatment between May 2008 and June 2010 (Table 4).

A cumulative P application of 2.5 g P m^{-2} to zoysiagrass (treatment 4) between May 2008 and June 2010 resulted in leached P exceeding the control treatment by 0.164 g P m^{-2} (Table 4). This cumulative application represents a mean P application per year of about 1.25 g P m^{-2}, which is greater than the maximum P application rate per year (1.07 g P m^{-2} yr^{-1}) permitted for turfgrass in the state of Florida.

Table 3. Comparison of leaf and root parameters, phosphorus uptake rate and Mehlich 1–extractable soil phosphorus between 'Empire' zoysiagrass and 'Floratam' St. Augustinegrass grown in the field on a low-phosphorus sand near Citra, Florida.

Parameters	Units	2008			2009			*P* value, 2008 vs. 2009	
		EZ†	SA‡	*P* value	EZ	SA	*P* value	EZ	SA
Leaf tissue P	g kg^{-1}	2.70	4.50	<0.0001	3.20	4.36	<0.0001	<0.0001	0.1934
Leaf growth rate	g DM§ m^{-2} d^{-1}	2.19	3.11	<0.0001	1.84	2.75	<0.0001	0.0732	0.0623
Leaf P uptake	mg m^{-2} d^{-1}	6.51	15.66	<0.0001	6.05	12.37	<0.0001	0.4922	0.0030
M1-P¶	mg kg^{-1}								
0–7.5 cm		4.09	2.88	0.0085	9.50	8.01	0.057	<0.0001	<0.0001
7.5–15 cm		2.77	1.83	0.0024	4.02	3.38	0.418	0.0272	0.0011
15–30 cm		–	–	–	1.84	0.69	0.0006	–	–
0–15 cm									
RDM#	g cm^{-3}	3.05	3.01	0.8325	1.79	2.22	<0.0001	<0.0001	0.0001
RLD††	cm m^{-3}	2.84	2.50	0.0065	1.26	1.21	0.1871	<0.0001	<0.0001
RSA‡‡	cm^2 cm^{-3}	0.34	0.38	0.0778	0.19	0.21	<0.0001	<0.0001	<0.0001
RV§§	mm^3 cm^{-3}	3.40	4.71	0.0012	2.26	3.05	<0.0001	<0.0001	<0.0001
RD¶¶	mm	0.38	0.49	<0.0001	0.47	0.56	<0.0001	0.0010	0.0493
15–30 cm									
RDM	g cm^{-3}	–	–	–	0.41	1.17	<0.0001	–	–
RLD	cm m^{-3}	–	–	–	0.56	0.81	<0.0001	–	–
RSA	cm^2 cm^{-3}	–	–	–	0.06	0.13	<0.0001	–	–
RV	mm^3 cm^{-3}	–	–	–	0.51	1.78	<0.0001	–	–
RD	mm	–	–	–	0.33	0.51	<0.0001	–	–

† 'Empire' zoysiagrass.

‡ 'Floratam' St. Augustinegrass.

§ Dry matter.

¶ Mehlich 1–extractable soil phosphorus values and root parameters data from the 15- to 30-cm depth corresponding to 2008 are not available.

Root dry matter accumulation (g DM cm^{-3} soil).

†† Root length density (cm root m^{-3} soil).

‡‡ Root surface area (cm^2 root cm^{-3} soil).

§§ Root volume (mm^3 cm^{-3}).

¶¶ Average root diameter (mm).

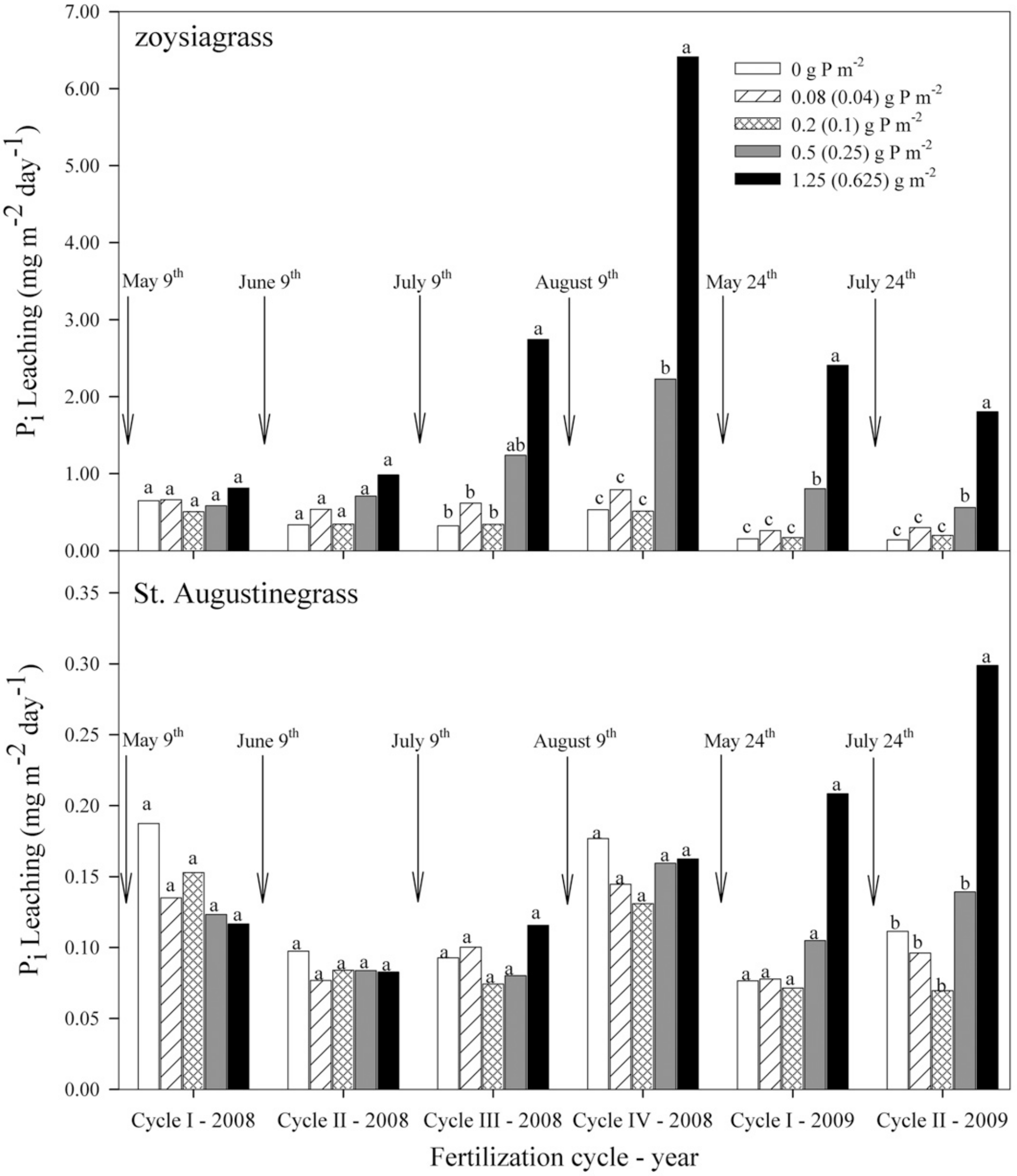

Fig. 1. Orthophosphate (dissolved inorganic phosphorus [P_i]) leaching rate from 'Empire' zoysiagrass and 'Floratam' St. Augustinegrass grown in the field on a low-P sand near Citra, Florida, as influenced by P application rate within each fertilizer application period during the first (2008) and second (2009) growing seasons. Fertilizer application dates are indicated by arrows. Phosphorus application rates outside parentheses correspond to 2008 (g P m^{-2} every 4 wk), and values within parentheses correspond to P application rates in 2009 (g P m^{-2} every 8 wk). The source of P was concentrated superphosphate (45% P_2O_5). Columns with the same letter within an application period are not significantly different at $P = 0.05$ according to single degree of freedom contrast analysis.

Discussion

Influence of Phosphorus Fertilizer on Selected Soil Chemical Properties

The negligible P retention capacity of the soil used in this study was likely related to the small fraction of clay-size particles and minor concentration of constituents such as kaolinite and gibbsite. Petrovic (2004) evaluated the influence of soil texture on the fate of N and P. The amount of P leached from Penncross creeping bentgrass (*Agrostis stolonifera* ssp. *palustris* Hud.) grown in sand was 3.5-fold greater than from turf grown in a silt loam and a sandy loam.

The reason for the increase in M1-P in the control treatments of both species from 2008 to 2009 is not clear. Verticutting at the beginning of the 2009 growing season could have favored mineralization of organic P in the thatch layer, which may have contributed to increase M1-P in the control plots during the 2009 growing season. The residual effects of continued P application and reduced P uptake rate during 2009 explain the increase in M1-P and PSR with time. Increased M1-P and PSR levels over time could have increased P_i concentrations in the soil solution and in leachates. The greater PSR observed during the second growing season may have favored downward movement of P, with percolating water resulting in increased P concentration deeper in the soil profile. Liu et al. (2009) reported increased M1-P concentrations with increasing P rates (0–1.07 g P m^{-2} every 4 wk for 12 wk) to 'Floratam' St. Augustinegrass grown under glasshouse conditions on Tavares sand (hyperthermic uncoated Typic Quartzipsamments) and Pottsburg sand (sandy, siliceous, Thermic Grossarenic Alaquod).

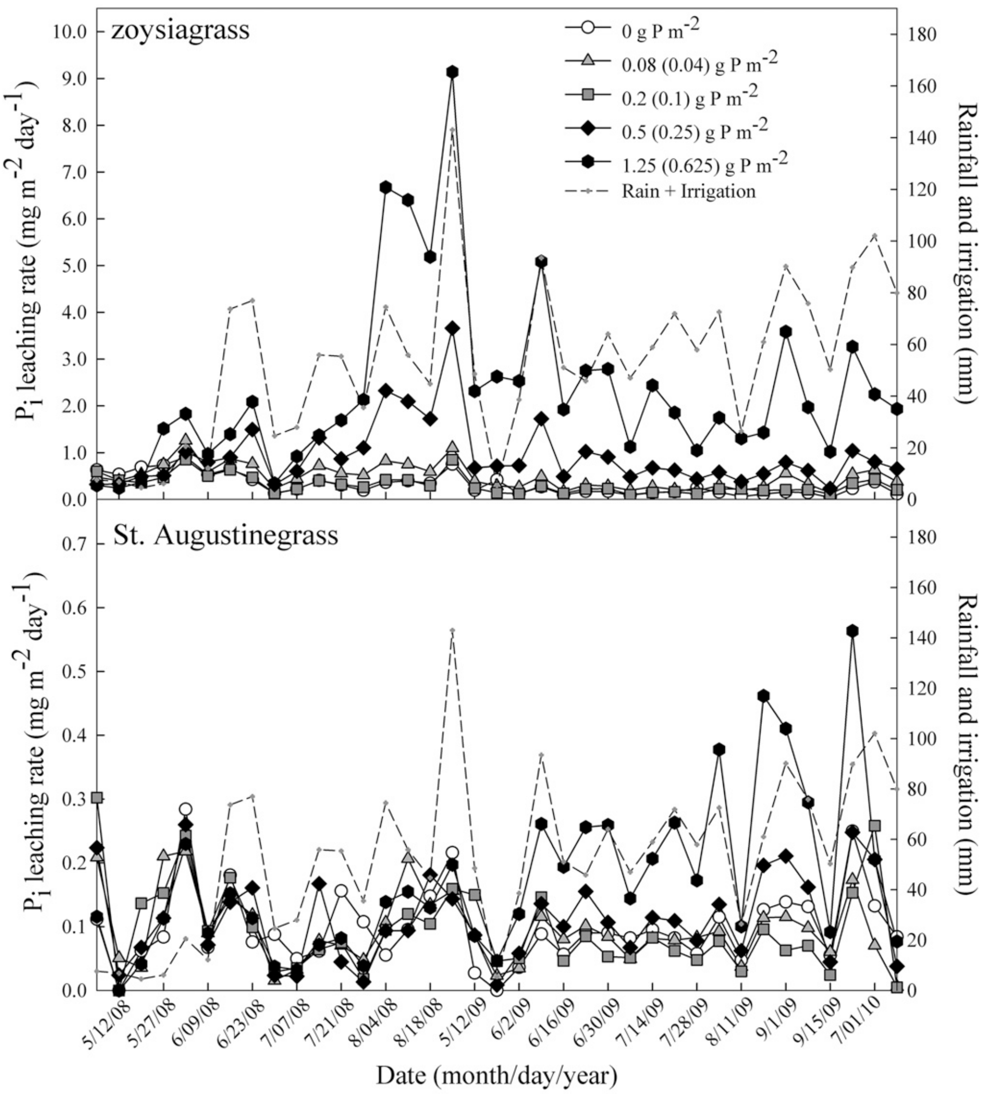

Fig. 2. Fluctuations in orthophosphate (dissolved inorganic phosphorus [P_i]) leaching rate and rainfall plus irrigation over time (May 2008 to July 2009) in 'Empire' zoysiagrass (above) and 'Floratam' St. Augustinegrass (below) grown in the field on a low-P sand near Citra, Florida. Phosphorus application rates outside parentheses correspond to 2008 (g P m^{-2} every 4 wk), and values within parenthesis correspond to P application rates in 2009 (g P m^{-2} every 8 wk). The source of P was concentrated superphosphate (45% P_2O_5).

The smaller M1-P and PSR values measured in soil under St. Augustinegrass could be explained by the greater P uptake rate of St. Augustinegrass. The greater P uptake of St. Augustinegrass could be associated to its larger and deeper root system, which is evidenced by the lower M1-P concentration within the 15- to 30-cm soil section observed in St. Augustinegrass plots. St. Augustinegrass may have been able to grow roots deeper into the soil profile due to the greater RD observed in this species. The root

Table 4. Cumulative orthophosphate (dissolved inorganic phosphorus) leached from fertilizer application in 'Empire' zoysiagrass and 'Floratam' St. Augustinegrass grown under field conditions on a low-P sand near Citra, Florida.

P rate†	Empire zoysiagrass				Floratam St. Augustinegrass			
	2008	2009	2010	Overall	2008	2009	2010	Overall
g m^{-2} applic.$^{-1}$		%‡		g P_i m^{-2}§		%		g P_i m^{-2}
0 (0)	–	–	–	–	–	–	–	–
0.08 (0.04)	7.24	9.33	10.31	0.041	−0.04	−0.20	−0.09	0.000
0.2 (0.1)	−0.50	−0.44	−0.17	−0.002	−0.12	−0.26	0.01	0.000
0.5 (0.25)	4.16	6.15	6.54	0.164	−0.04	0.11	0.25	0.006
1.25 (0.625)	4.83	8.29	8.93	0.558	−0.02	0.36	0.41	0.026

† Values outside parentheses correspond to P application rates during 2008 (g P m^{-2} every 4 wk). Values within parentheses correspond to the P application rates during 2009 (g P m^{-2} every 8 wk). The source of P was concentrated superphosphate (45% P_2O_5). No P application was conducted during 2010, but orthophosphate leached until June 2010 is included in the calculations.

‡ Percent of cumulative P applied leached over the control treatment.

§ Grams of orthophosphate leached over the control treatment per m^2 between May 2008 and June 2010.

parameter that appeared to be more closely related to differences in P uptake rate between St. Augustinegrass and zoysiagrass was RV because this root parameter differed the most between species in both evaluation years and sampling depths. The greater P uptake rate measured in St. Augustinegrass was also associated with greater leaf growth rate and greater P concentration in leaf tissue. Higher PSR in the soil under zoysiagrass could favor greater P leaching from this turfgrass compared with St. Augustinegrass when exposed to same growing conditions and P fertilizer supply.

Several authors have reported increases of dissolved reactive P concentrations in leachates and runoff with increasing soil test P (Heckrath et al., 1995; Pote et al., 1999; Hesketh and Brookes, 2000; Maguire and Sims, 2002b). Continued P application over time to home lawn turfgrasses grown in soils with limited P retention capacity, like the low-P sand used in this study, would increase the soil test P and PSR, resulting in greater risk of increased P leaching.

Orthophosphate Leaching Rate

Phosphorus release during thatch layer decomposition in addition to P release by the soil represent potential sources of P_i leaching from unfertilized turf. Greater release of inorganic P from mineralization of the larger zoysiagrass thatch layer may explain the greater P_i leaching measured from the control treatment in this species.

The lower P_i leaching rate from St. Augustinegrass could be explained by its greater P uptake rate and P accumulation, which may have resulted in lower soil test P and lower P_i concentration in the soil solution from where it would be prone to leaching. The larger and deeper root system of St. Augustinegrass likely allowed it to recover more P from solution as P_i was carried downward by percolating water. In a study with six warm-season turfgrass species, Bowman et al. (2002) found that nitrate-nitrogen leaching was least from 'Raleigh' St. Augustinegrass and greatest from 'Meyer' zoysiagrass. Nitrate leaching was inversely related to root length density at depths >30 cm (Bowman et al., 2002). In the event of high rainfall or excessive irrigation after fertilization, a more extensive and deeper root system would favor greater uptake efficiency and less leaching of applied P fertilizer.

Gonzalez (2010) conducted a hydroponic study to evaluate the whole-plant P depletion rate from solution by 'Floratam' St. Augustinegrass and 'Empire' zoysiagrass. St. Augustinegrass absorbed P from solution at a faster rate than zoysiagrass. The P depletion rate from solution decreased with increasing leaf tissue P concentration in zoysiagrass but was unaffected in the case of St. Augustinegrass. Faster P depletion from solution by St. Augustinegrass likely reduced P leaching.

The combined effects of lower P uptake, greater M1-P and PSR values, and greater rainfall during 2009 likely explain the substantial reduction in the maximum P application rate that could be supplied to zoysiagrass and St. Augustinegrass without increasing P leaching during the second growing season. Nutrient uptake rates increase with increasing plant growth rate. Phosphorus fertilizer application should be conducted during periods when P uptake rate is highest, especially when turf is grown in soils with limited available P retention capacity. A high plant P uptake rate could compensate for abrupt increases in the soil solution P concentration after P fertilization and reduce the risk of P leaching. Accurate P fertilization timing could reduce leaching by increasing P uptake and accumulation in the plant.

Soil test P alone was insufficient to assess the risk of P leaching in this study. On average, M1-P did not surpass 10 mg kg^{-1} soil, which is interpreted as very low in Florida (Mylavarapu et al., 2009); however, P_i leaching from some of the fertilized treatments was greater than from the control treatment. Therefore, the use of an index that incorporates the ability of the soil to retain P, such as the PSR, would allow a better assessment of the risk of P leaching from soil under these turfgrasses. Soil P supply to turf growing in a soil saturated with P would likely be sufficient for adequate plant growth, and no P fertilization would be required. Examples of this condition are the zoysiagrass and St. Augustinegrass control treatments in which the P concentration in leaf tissue remained above the critical concentration for the duration of the study.

Only a small fraction of the P fertilizer applied to these turfgrass species was leached. Clearly, P fertilization rates should be tailored to meet turf species–specific requirements and species' ability to take up and accumulate P to avoid increased P losses. Determining a threshold P application rate to minimize P leaching from zoysiagrass and St. Augustinegrass should incorporate the assessment of an array of variables, such as PSR, plant nutritional status, overall condition and health of the turf, application timing, precipitation distribution and intensity, and irrigation rate. The combination of soil, plant, weather, and management conditions present in this study were highly conducive to P leaching. In a turfgrass stand with P concentration in leaf tissue near the critical level for maximum growth, grown in a soil with P retention capacity that is not overirrigated, the risk of increased P leaching as a result of P fertilization would be much lower than that in a turfgrass system like the one used in this study.

Conclusions

Home lawn warm-season turfgrasses can be fertilized without increasing the risk of P leaching to groundwater. Phosphorus fertilizer application rate should be reduced to minimize P loss if plant P uptake decreases and the soil has limited P retention capacity. Excessive irrigation and fertilization when the risk of heavy rainfall is imminent may contribute to increase P leaching. If tissue analysis indicates that P fertilization is required and the soil PSR is less than the threshold value that relates to increased P in solution, a maximum P application of 0.8 g m^{-2} yr^{-1} to zoysiagrass and 1.07 g m^{-2} yr^{-1} to St. Augustinegrass would not increase P_i leaching. Continued P fertilization at these rates to zoysiagrass and St. Augustinegrass grown in soils with limited P retention capacity and with a leaf tissue P concentration greater than the critical could lead to increased P_i leaching.

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