Growth, Cover, and Quality of St. Augustinegrass and Zoysiagrass Relative to Leaf Phosphorus Concentration in Hydroponic Culture

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

ABSTRACT

Limited information on critical leaf tissue P concentration of home lawn warm season turfgrasses is available. This study was conducted to determine the critical P concentration in leaf tissue of 'Floratam' St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] and 'Empire' zoysiagrass (*Zoysia japonica*). The leaf tissue P concentration (TP) that relates to maximum leaf growth rate (GR), visual quality and percent green turf cover (GC) was studied under glasshouse conditions using a continuous flow hydroponic system. Six levels of P were supplied (0, 90, 135, 203, 304, 456 mg P m^{-3}) as $KHPO_4$. Maximum zoysiagrass (EZ) leaf growth rate was attained at solution P and leaf tissue P concentrations of 382 mg P m^{-3} and 1.67 g P kg^{-1}, respectively. St. Augustinegrass (SA) leaf growth rate reached a maximum at a P concentration in solution and a TP concentration of 374 g P m^{-3} and 1.73 g P kg^{-1}, respectively. Visual quality of SA increased linearly with increasing TP and EZ visual quality reached a maximum at 1.7 g P kg^{-1}. Percent green turf cover increased quadratically with increasing TP attaining a maximum at 1.35 g P kg^{-1} for EZ and 1.48 g P kg^{-1} for SA. A positive quadratic relationship between GC and GR was observed in both species. Consequently, a TP of 1.35 and 1.67 g P kg^{-1} for EZ and 1.48 and 1.73 g P kg^{-1} for SA could be used as the threshold concentrations for maintenance of maximum GC and maximum growth and recovery rate, respectively.

R.F. Gonzalez, J.B. Sartain and G.A. O'Connor, Soil and Water Science Dep., Univ. of Florida, P.O. Box 110510, Gainesville, FL 32611; 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. Received _____. *Corresponding author (rfgonzalez@ufl.edu).

Knowledge of critical P concentration of turfgrasses is crucial for adequate P fertilization. The critical nutrient concentration has been defined as the nutrient concentration in diagnostic tissues below which plant growth or yield response to increased nutrient concentration or nutrient supply is observed (Havlin et al., 1999). Therefore, P fertilization is not recommended when the P concentration in leaf tissue is equal or greater than the critical concentration.

Excessive P fertilization to turfgrass can lead to increased P losses to the environment through runoff and leaching (Shuman, 2002; Guertal, 2007; Soldat and Petrovic, 2008). Eutrophication of P-limited surface water bodies has been linked to enrichment of the water column with P from anthropogenic sources (Correll, 1998; Carpenter et al., 1998; Foy, 2005).

In Florida, 'Floratam' SA is the most widely cultivated turfgrass species. Zoysiagrass occupies the fourth largest area of sod production in Florida and Empire is the predominant cultivar of this species in the state (Satterthwaite et al., 2007). These turfgrass species are mainly used in lawns (Trenholm and Unruh, 2005). Limited information on the critical leaf tissue P concentrations of these turfgrass species is currently available.

Cisar et al. (1992) conducted a field study to evaluate the response to N, P and K fertilization on 'Floratam' St. Augustinegrass grown in a Lauderhill muck soil (Euic, hyperthermic Lithic Medisaprist). They reported an increase in sod quality, turf quality and clippings biomass accumulation of 'Floratam' SA in response to P fertilization when the P concentration in tissue was below approximately 2.4 g P kg^{-1}.

Liu et al. (2006) studied the response in terms of growth and quality of 'Floratam' SA to P supply in solution culture within a P concentration range of 0 to 775 mg P m^{-3}. Maximum growth rate was reached at a leaf tissue P concentration of 1.6 g P kg^{-1}, which was attained at 111 mg P m^{-3}. Turf quality continued to increase with increasing supply up to 775 mg P m^{-3}. This

study was conducted during the period of the year of lower temperature and solar radiation (October to March) which could have affected the turfgrass growth rate and P uptake as well as the tissue P concentration. 'Floratam' St. Augustinegrass grown in sandy soils (Alaquods and Quartzipsamments) under glasshouse conditions reached maximum top growth at a leaf tissue P concentration of 1.8 g P kg^{-1} (Liu et al., 2008). The leaf tissue P concentration that resulted in maximum SA turf quality was not identified in these studies.

The determination of critical P concentration in leaf tissue should incorporate measures of turf quality and turf cover as response variables. Turfgrass cover is a major component of turfgrass aesthetics. Green turfgrass cover can be accurately and precisely measured with digital image analysis (Richardson et al., 2001).Vigorous turfgrass growth is desirable for faster recovery after periods of stress, but excessive biomass accumulation rate could result in greater maintenance requirements and expense. Phosphorus supply in a 1:1:1 $N:P_2O_5:K_2O$ ratio increased 'Floradwarf', 'Tifdwarf', and 'TifEagle' bermudagrasses (*C. dactylon* x *C. transvaalensis*) cover ratings in comparison to treatments that did not receive P application (Rodriguez et al., 2000).

The objectives of this study were to determine the critical P concentrations in leaf tissue of SA and EZ based on leaf growth rate, visual quality and percent green turf cover and to evaluate the applicability of digital image analysis in turfgrass nutrient response studies.

MATERIALS AND METHODS

Hydroponic System Description and Experimental Design

The study was conducted in the Turfgrass Envirotron facility on the University of Florida campus (29° 38' N, 82° 21' W) under glasshouse conditions. Average relative humidity and temperature in the glasshouse were 70% and 28.4 °C, respectively. The relative humidity and the temperature oscillated between 20% and 89% and 21°C and 39°C, respectively. In addition, the average photosynthetic photon flux density (measured outside the glasshouse) between 0700 and 1800 h was 898 µmol m^{-2} s^{-1} and ranged from 1.63 to a 2,459 µmol m^{-2} s^{-1}. *Zoysia japonica* 'Empire' (EZ) and *Stenotaphrum secundatum* (Walt) Kuntze 'Floratam' (SA) certified sod from the G.C. Horn Turfgrass Field Laboratory near Citra, Florida were selected as the test cultivars. The sod was washed thoroughly to remove soil from the root system, cut into 20 cm x 33 cm rectangles and transferred to a hydroponics system. Polyvinyl chloride (PVC, 22 mm outer diameter) pipe was used to construct a 22 cm by 33 cm frame and covered with poly hardware cloth (13-mm square openings). The sod was placed on the plastic screen which was used as a grass bedding surface. Turf roots were carefully passed through the openings of the plastic screen to promote contact with the nutrient solution. Each experimental unit was placed on a 25 cm x 36 cm x 23 cm plastic tub (~20 L) used as the hydroponic container. The tubs corresponding to a given treatment were connected to a larger nutrient reservoir (120 L). A submersible pump delivered nutrient solution to the corresponding tubs at a rate of 12 L per minute and the solution returned to the nutrient solution reservoir by gravity; hence, the nutrient solution was constantly circulating between the tubs and the nutrient solution reservoir.

Light penetration through the outer surfaces of the tubs was restricted by black latex paint. During the first two weeks of the experiment, the nutrient solution level was maintained in

contact with the plastic hardware net to stimulate root growth. Thereafter, the solution level was lowered to about 2.5 cm from the plastic screen to favor incorporation of oxygen as the continually circulating solution entered in contact with the solution present in the tub. The turfgrass was maintained from December 19th 2008 until May 24th 2009 on a modified half strength Hoagland solution (Hoagland and Arnon, 1950) without P to reduce tissue P levels. Phosphorus treatments were imposed on May 24th, 2009 and the study was continued for 140 days thereafter. Six levels of P (0, 90, 135, 203, 304 and 456 mg P m^{-3}) were supplied with reagent grade mono potassium phosphate (22.6 % P) in a modified full strength Hoagland (Hoagland and Arnon, 1950) nutrient solution. The P treatments were replicated five times and arranged in a split-plot randomized complete block design with turfgrass species as the main effect and P application rate as secondary effect. The initial concentrations of NH_4-N, NO_3-N, K, Ca, Mg, and S in the nutrient solution were 7.5, 7.5, 6, 2, 2, and 2 m*M*, respectively. The initial solution concentrations of Mn, Zn, Cu, B, and Mo were 9, 1.5, 1.5, 45 and 0.1 µ*M*, respectively. Chelated iron (Sequestrene 330) was supplied biweekly through foliar application at a rate of 0.5 g Fe m^{-2} (Carrow et al., 2001). The nutrient solution was replaced twice per week. Initial solution pH oscillated between 5.5 and 6 and the initial nutrient solution temperature ranged between 25°C and 30 °C.

Tissue Sampling and Analysis, Turf Quality and Chlorophyll Index

Top growth was harvested every two weeks to a height of about 10 cm. Roots were clipped to about 10 cm when their length was roughly 15 cm. All tissue samples were oven-dried at 70°C to constant weight, weighed, and then ground to pass a #40 (425 µm opening size) sieve. Dry tissue (DM) was ashed and digested according to Andersen (1976). Phosphorus concentration in the digestate was determined by colorimetry following the procedure described by O'Dell (1993).

Leaf and root tissue growth rate (g DM m^2 d^{-1}) was monitored during the entire evaluation period. Turf visual quality was evaluated biweekly using a scale of 1 to 9, where 1 represents brown, dormant turf and 9 represents superior quality. A value of 5.5 was considered the minimum rating for an acceptable turf visual quality (Skogley and Sawyer, 1992). Chlorophyll Index (*Ci*) was measured biweekly with a CM 1000 Chlorophyll Meter (Spectrum Technologies Inc, Illinois, USA) immediately prior every leaf tissue harvest. The *Ci* is obtained by comparing the ratio of the 700 nm and 840 nm in available light (ambient light) to the ratio of the same wavelengths of reflected light. The *Ci* is reported in a scale of 0 to 999 (Spectrum Technologies Inc, CM 1000 chlorophyll meter manual, 2009).

Green Turf Cover

Percent green turf cover was measured with digital image analyses. Digital images were obtained with a Canon PowerShot A630 (Canon Inc., New York, USA) digital camera mounted on a light box constructed to fit exactly over the tubs utilized as hydroponic containers. The dimensions of the light box were 25 cm x 36 cm x 30 cm. The bottom side of the light box was open to allow placement over the turf, and a 38 mm diameter opening was drilled in the upper side of the light box to accommodate the camera lens. A 13 W compact fluorescent (day-light) bulb on one side of the light box provided uniform light intensity.

Leaf tips were trimmed to approximately the same height (about 15 cm) in all treatments prior collecting the digital images. The images obtained were saved in JPEG format with an image size of 5 mega pixels (2,592 by 1,944 pixels). Camera settings consisted of an exposure time of 1/13 seconds, an aperture of F8, and a focal length of 7 mm. All digital images were resized to 800 by 600 pixels using ACDSee Pro (v. 2.5, ACDSee Systems International Inc., Victoria, British Columbia, Canada). The digital images were analyzed using SigmaScan Pro (v.

5.0, SPSS Inc., Chicago, IL) and the "turf analysis macro" (Karcher and Richardson, 2005) for batch analysis of turf digital images. The color threshold settings were a hue range from 50 to 107 and a saturation range from 0 to 100, which selectively identified green pixels in the images. The turf analysis macro calculated the percent green turf cover by dividing green pixels by the total number of pixels in each image.

Statistical Analyses

Non linear regression analyses (Proc Reg) in SAS statistical software v. 9.2 (SAS Institute, 2009) was used to relate response variables (i.e., leaf growth rate, turf visual quality, and percent green turf cover) to explanatory variables (leaf tissue P concentration, and initial solution P concentration). The level of a given explanatory variable at which the first derivative of second order polynomial equations relating response and explanatory variables equaled zero, was defined as the critical level for that independent variable. The general linear model procedure (Proc GLM) of SAS was used to conduct analysis of variance and mean separation was carried out using single degree of freedom contrast analysis.

RESULTS

Phosphorus Concentration in Leaf and Root Tissue

The average P concentration in leaf tissue following turf establishment in the hydroponic system was 1.9 g P kg^{-1} for EZ and 3.4 g P kg^{-1} for SA (Table 1). Average leaf tissue P concentration immediately prior to imposing the P treatments was 0.64 g P kg^{-1} in EZ and 0.28 g kg^{-1} in SA (Table 1). Leaf P concentration increased linearly with increasing P supply at a rate of about 3 mg P kg^{-1} per mg P m^{-3} of solution ($r^2>0.94$, $p<0.0001$, CV<9%). Root tissue P concentrations in EZ and SA across treatments immediately prior imposing the P treatments were 0.49 g P kg^{-1} and 0.45 g kg^{-1}, respectively. Leaf tissue P concentration in the control treatment decreased over time in EZ and increased in SA (Table 1). Across sampling times, P

concentrations in EZ and SA root tissue of the control treatment were lower than in root tissue supplied with P. However, P concentrations in root tissue of turf supplied with P remained fairly similar regardless of the P supply rate (Fig. 1). Zoysiagrass root tissue P concentration in the control treatment decreased by 35% during the evaluation period (140 days), while the P concentration of roots in the other treatments did not decrease. Root tissue P concentration in SA grown in the control treatment decreased 22% during the evaluation period. Tissue P concentration increased over time at a rate (mg P kg^{-1} day^{-1}) up to 5 and 15 times greater in leaves than in roots of EZ and SA, respectively.

Leaf and Root Growth Rate

Zoysiagrass root growth rate did not show a clear response to P supply rate (Fig. 1); however, an initial P concentration in solution of 203 and 304 mg P m^{-3} resulted in a root growth rate 24% and 43% greater than in the control treatment, respectively. Even though not significantly different from the control treatment, an initial P supply of 456 mg P m^{-3} produced the least EZ root growth (Fig. 1). In contrast, the greatest EZ leaf tissue growth rate was attained in this treatment. Maximum EZ root growth rate corresponded to a root tissue P concentration of 0.62 g P kg^{-1}, which was only 37% of the leaf tissue P concentration (1.67 g P kg^{-1}) required for maximum leaf growth rate. St. Augustinegrass root tissue P concentration and root growth rate increased quadratically with increasing P supply (Fig. 1). A maximum root growth rate of 0.37 g m^{-2} day^{-1} was obtained in SA turf exposed to an initial P concentration of 304 mg P m^{-3}; however, root growth rate did not increase beyond an initial P solution concentration of 203 mg P m^{-3} (Fig. 1). Maximum SA root growth rate corresponded to an average tissue P concentration of 0.97 g P kg^{-1} DM, which was 44% lower than the leaf tissue P concentration (1.73 g P kg^{-1} DM) required for maximum leaf growth rate.

Leaf growth rates of EZ and SA, increased with increasing leaf tissue P concentration to a maximum growth rate of about 13 g dry matter m^{-2} day^{-1} (Fig. 2). Maximum growth rates were obtained at leaf tissue P concentrations of 1.67 g P kg^{-1} for EZ and 1.73 g P kg^{-1} for SA (Fig. 2). Greater P supply increased leaf tissue growth rate (Fig. 2). Average maximum growth rates were 13.4 g DM m^{-2} day^{-1} at 382 mg P m^{-3} for EZ, and 13.45 g m^{-2} day^{-1} at 374 mg P m^{-3} for SA (Fig. 2).

A positive linear relationship between *Ci* and leaf tissue P concentration was observed in both turfgrass species (r^2>0.70, p<0.0001, CV<17%). Zoysiagrass leaf growth rate increased quadratically with increasing *Ci* reaching a maximum at a *Ci* value of 641 (Fig. 2). St. Augustinegrass leaf growth rate increased linearly with increasing *Ci* (Fig. 2).

Green Turf Cover

Percent green turf cover was positively related to leaf tissue P concentration in both turfgrass species (Fig. 3). A maximum GC of 92% was attained at a critical leaf tissue P concentration of 1.35 g P kg^{-1} in EZ, and a maximum GC of 80% at 1.48 g P kg^{-1} in SA (Fig. 3). Percent green turf cover increased quadratically to a maximum of 93.5% observed at an initial solution P concentration of 303 mg P m^{-3} in EZ, and 82% at 335 mg P m^{-3} in SA (Fig. 3). Percent green turf cover increased with increasing *Ci* (Fig. 3).

A positive quadratic relationship between percent green cover and growth rate was observed (Fig. 3). Maximum GC (92%) was attained at a leaf growth rate of 10.4 g DM m^{-2} day^{-1} in EZ, and a maximum GC of 80% was reached at 10.5 g DM m^{-2} day^{-1} in SA. Leaf growth rate continued to increase beyond the critical leaf tissue P for maximum GC and reached a plateau at a leaf tissue P concentration that was 0.32 g P kg^{-1} and 0.25 g P kg^{-1} greater than that required for maximum GC in EZ and SA, respectively (Fig. 3). No additional increase in GC was obtained above a leaf growth rate of 10.5 g m^{-2} day^{-1} in either turfgrass species (Fig. 3).

Percent green turf cover was significantly related to leaf tissue P, initial solution P concentration and *Ci*. Overall, the coefficients of variation (CV) for the relationships between leaf growth rate as the response variable and the explanatory variables evaluated were greater than when GC was used as the response. In most cases, the independent variables explained a slightly greater amount of the variability on leaf growth rate than on GC.

Turf Quality

A positive quadratic response was obtained when EZ visual quality ratings were regressed against leaf tissue P concentrations (Fig. 4). Zoysiagrass visual quality reached a maximum at a leaf tissue P concentration of 1.7 g P kg^{-1}, which corresponded to a maximum visual quality rating of 8.7. St. Augustinegrass visual quality increased linearly with increasing leaf tissue P concentration (Fig. 4). Liu et al. (2006) reported continuously increasing in St. Augustinegrass visual quality with increasing P supply from 0 mg P m^{-3} to 775 mg P m^{-3}. Leaf tissue P concentrations of 0.45 g P kg^{-1} for EZ and 1.15 g P kg^{-1} for SA were required to attain visual quality ratings of 5.5, which is broadly used as the minimum rating for acceptable turf quality.

Turf visual quality increased with increasing P supply (Fig. 4). Initial solution concentrations of 90 mg P m^{-3} and 203 mg P m^{-3} were required to increase EZ and SA visual quality above a rating of 5.5, respectively. Maximum EZ visual quality was obtained at an initial P solution concentration of 370 mg P m^{-3} (Fig. 4). Visual quality of St. Augustinegrass increased with increasing P supply from a minimum of 4.4 in the 0 mg P m^{-3} treatment to a maximum of 6.7 in turf exposed to an initial P concentration in solution of 456 mg P m^{-3} (Fig. 4).

Zoysiagrass visual quality rating increased quadratically with increasing *Ci* to a maximum rating of 8.7, which was attained at a *Ci* of 654 (Fig. 4). St. Augustinegrass turf visual quality increased linearly in response to *Ci* (Fig. 4). About 33% and 57% of the turf leaf tissue growing in the control treatment of EZ and SA, respectively, was dead by the end of the evaluation

period. Acceptable turf visual quality was attained at a *Ci* value of 304 in EZ and a 319 in the case of SA (Fig. 4).

DISCUSSION

Growth Rate and Tissue Phosphorus Concentration

Increased growth rate in response to greater radiation flux as the growth season progressed in addition to limited P supply and uptake could have resulted in P dilution and may explain the decrease in EZ leaf tissue P concentration overtime in the 0 and 90 mg m^{-3} P treatments. Release of P from the thatch layer into solution and the positive effect of adequate supply of macronutrients and micronutrients on root growth, may have favored P uptake, and increased the leaf tissue P concentration of SA in the 0 mg P m^{-3} treatment. Translocation of P to slow growing young tissue, such as that observed in P deficient plants, may result in increased P concentration. Phosphorus may be translocated from older to younger plant tissues, especially when the P supply and uptake is insufficient to meet the demand of young tissues (Mengel and Kirkby, 2001). The rate of P accumulation in roots was lower in SA than in EZ, suggesting that under P deficiency, a greater fraction of the P absorbed is partitioned to aboveground tissues (i.e., stolons and leaves) in SA than in EZ.

Increasing P supply resulted in greater root growth rate only in SA. Greater root growth in response to increased P supply from the soil or fertilizers, could allow SA to absorb a greater fraction of available P; hence, reducing the risk of P losses to the environment. Root tissue P concentration did not differ significantly among turf supplied with increasing P rates. Liu et al. (2006) reported significant increase in SA root tissue P concentration in response to increasing P supply in solution culture raging from 0 to 775 mg P m^{-3}. In addition to differences in P application rates, the maximum shoot growth rate in Liu et al. (2006) study was 1 g DM m^{-2} day^{-1}

compared to 13 g DM m^{-2} day^{-1} measured in this experiment. Greater shoot P demand may have limited the P concentration in root tissue in response to increasing P supply.

Aboveground tissue growth rate increased quadratically with increasing P supply and leaf tissue P concentration. Liu et al. (2006) observed a positive quadratic response of Floratam St. Augustinegrass aboveground tissue growth rate in response to increasing P supply and leaf tissue concentration. The critical leaf tissue P concentration in their study was 1.6 g P kg^{-1}. Moreover, Liu et al. (2008) reported that the critical leaf tissue P concentration for maximum top growth of SA grown under glasshouse conditions in four different soils was 1.8 g P kg^{-1}. The critical leaf tissue P concentration for maximum aboveground tissue growth rate indentified in this experiment for SA (1.73 g P kg^{-1}), is in agreement with results previously reported by others (Liu et al., 2006; Liu et al., 2008).

Reports of critical leaf tissue P concentration for EZ were not found. Juska (1959) observed a positive effect of P supply on 'Meyer' zoysiagrass (*Zoysia japonica*) top growth; however, the critical leaf tissue P concentration was not identified in that study. Andrew and Robins (1971) evaluated the growth response of nine tropical grasses to P supply in order to determine the critical tissue P concentrations, and indicated that the critical tissue P concentrations ranged from 1.6 g P kg^{-1} to 2.5 g P kg^{-1}. No significant yield increase of 'Pensacola' bahiagrass (*Paspalum notatum*) was observed above a leaf tissue P concentration of 1.5 g P kg^{-1} (Burton et al., 1997).

Growth rate of aboveground tissues increased with increasing *Ci* values. Madison and Andersen (1963) observed greater fresh biomass of 'Seaside' bentgrass (*Agriostis palustris Huds*.) and 'Highland' bentgrass (*Agriostis tenuis* Sibth.) with greater levels of extracted chlorophyll (mg dm^{-2}). Mangiafico and Guillard (2005) reported a positive relationship (R^2=0.79, $p<0.0001$) between extractable chlorophyll concentration (mg g fresh wt.) and *Ci* (measured with

the Spectrum Field Scout CM 1000 chlorophyll meter) under field conditions in a 90% 'Kentucky' bluegrass (*Poa pratensis* L.) and 10% creeping red fescue (*Festuca rubra* L.) turfgrass mixture. Moreover, dry matter yield increased with increasing *Ci* (Mangiafico and Guillard, 2005).

Green Turf Cover

Richardson et al. (2001) showed that DIA can accurately and precisely quantify green turf cover. Other authors have reported that DIA can accurately measure percent green leaf cover in soybeans (Purcell, 2000) and wheat (Lukina et al., 1999).

The critical leaf tissue P concentrations for EZ (1.67 g P kg^{-1}) and SA (1.73 g P kg^{-1}) (Fig. 1), corresponded to maximum leaf growth rate of about 13 g m^{-2} day^{-1}. This leaf growth rate was related to a maximum GC of 89% in EZ and 77% in SA (Fig. 3). Maximum GC (92%) was attained at 1.35 g P kg^{-1} in EZ, and a maximum GC of 80% was reached at 1.48 g P kg^{-1} in SA (Fig. 3). Hence, critical leaf tissue P concentrations obtained using leaf growth rate and GC as the response variables were in agreement because they were related to basically the same maximum GC (i.e., 3 % difference in GC estimates).

In healthy, high quality turfgrass stands that are adequately supplied with water and nutrients, leaf tissue P concentrations of 1.35 g P kg^{-1} in EZ and 1.48 g P kg^{-1} in SA could be used to maintain high quality and maximum percent green cover, without the potential inconvenience of excessive growth and greater maintenance requirements (i.e., greater mowing frequency). According to non-linear regression analysis the estimated difference in EZ turf visual quality that relates to a leaf tissue P concentration of 1.35 g P kg^{-1} (i.e., critical leaf tissue P determined with GC as the response) versus that obtained at 1.67 g P kg^{-1} (i.e., critical leaf tissue P determined with leaf growth rate as the explanatory variable) was only 0.21 turf visual quality

rating units. The difference in SA visual quality related to a critical leaf tissue P concentration for maximum GC (1.48 g P kg^{-1}) versus that attained at critical concentration for maximum aboveground tissue growth rate (1.73 g P kg^{-1}) was 0.5 turf visual quality rating units. These differences in turf visual quality can be neither accurately nor precisely distinguished even by an experienced evaluator and most certainly among different evaluators and evaluation sites.

Alternatively, in low quality, low density stands that had been affected by pest or disease infections or that had received heavy loads of traffic, a leaf tissue P concentration of 1.67 g P kg^{-1} in EZ and 1.73 g P kg^{-1} in SA could be used to maximize leaf growth rate and turf recovery rate. Phosphorus fertilization should be conducted only after the source of stress has been completely controlled (e.g., after water stress or a disease outbreak has been completely controlled) and if the leaf tissue P concentration is less than the critical. Accordingly, the diagnosis of the P nutritional status of these turfgrass species should incorporate an assessment of the overall health and condition of the turf and also the quality and density that the turfgrass stand is expected to reach and maintain over time.

The increase in GC of both species observed in this study with increasing *Ci* is in agreement with the results of Ma et al. (1996), who found a positive relationship between the product of leaf area and chlorophyll content with canopy reflectance of corn plants. Visual density ratings of Seashore paspalum (*Paspalum vaginatum* Swartz) and bermudagrass (*Cynodon dactylon* L. x *C. transvaalensis* Burtt-Davy) increased linearly with increasing canopy reflectance ratio expressed as normalized difference vegetation index (NDVI) (Trenholm et al. 1999).

The strong relationship between leaf growth rate and GC, the lower variability of the GC data in comparison to the leaf growth rate data and the robust relationship between GC and the

explanatory variables evaluated in this study, indicate that GC, as measured with DIA, can be effectively utilized in turfgrass nutrient response experiments.

Turfgrass Visual Quality

Zoysiagrass turf visual quality attained in this experiment was excellent, as reflected by the plateau from the relationship between visual quality rating and leaf tissue P, which is only 3% below the maximum possible rating (i.e., 9) in the scale utilized in this study. The substantial amount of brown, dead turf in the 0 mg P m^{-3} treatment may have caused a reduced *Ci* reading from turfgrass in this treatment. Menn and Mcbee (1970) reported that foliage of 'Tifway' bermudagrass (*Cynodon dactylon* x *C. transvaalensis* L.) supplied with low P in hydroponic culture initially turned dark green but later changed to a pale green color. They observed a decrease in foliage growth and color change below a leaf tissue P concentration of 2 g P kg^{-1}, and suggested that above this leaf tissue P concentration the aesthetic value of Tifgreen bermudagrass would be adequate.

St. Augustinegrass and EZ visual quality increased with increasing P supply and the concomitant increase in leaf tissue P concentration. Visual quality of creeping bentgrass (*Agriostis stolonifera* Huds.) increased quadratically with increasing leaf tissue P concentration (Johnson et al., 2003). Liu et al. (2006) observed an increase in visual quality with increasing P supply in hydroponic culture.

Empire zoysiagrass visual quality ratings and leaf growth rate increased with increasing *Ci* to a maximum attained at about the same *Ci* value. Seashore paspalum and bermudagrass visual quality ratings increased linearly with increasing canopy NDVI (Trenholm et al. 1999). Rodriguez and Miller (2000) found a linear relationship (r^2=0.79, $p<0.0001$) between chlorophyll readings as measured with a SPAD-502 chlorophyll meter and extracted chlorophyll

concentration (g kg^{-1} fresh tissue) from SA leaves. They also reported that visual quality ratings of SA increased linearly with increasing chlorophyll readings (r^2=0.74, p<0.0001). Visual quality ratings of Seaside bentgrass and Highland bentgrass increased linearly with increasing extractable chlorophyll concentration (Madison and Andersen, 1963).

CONCLUSIONS

Leaf growth rate increased quadratically with increasing leaf tissue P concentration. The critical leaf tissue P concentration for maximum leaf growth rate was 1.67 g P kg^{-1} and 1.73 g P kg^{-1} for EZ and SA, respectively. Digital image analysis could precisely measure differences in GC associated with changes in leaf tissue P concentration. Percent green turf cover increased quadratically with increasing leaf tissue P. The critical leaf P concentration for maximum growth rate was also sufficient to promote maximum GC in both species. Maximum GC was attained at 1.35 g P kg^{-1} in EZ and 1.48 g P kg^{-1} in SA. Consequently, a P concentration in leaf tissue of 1.35 g P kg^{-1} and 1.67 g P kg^{-1} in the case of EZ and 1.48 g P kg^{-1} and 1.73 g P kg^{-1} for SA could be used as the threshold concentrations for maintenance of maximum green turf cover and maximum growth and recovery rates, respectively. Based on the results of this study, P fertilization to EZ and SA would not be recommended if the leaf tissue P concentration is greater than 1.7 g P kg^{-1}.

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Table 1. Tissue P concentration as influenced by phosphorus application rate over time.

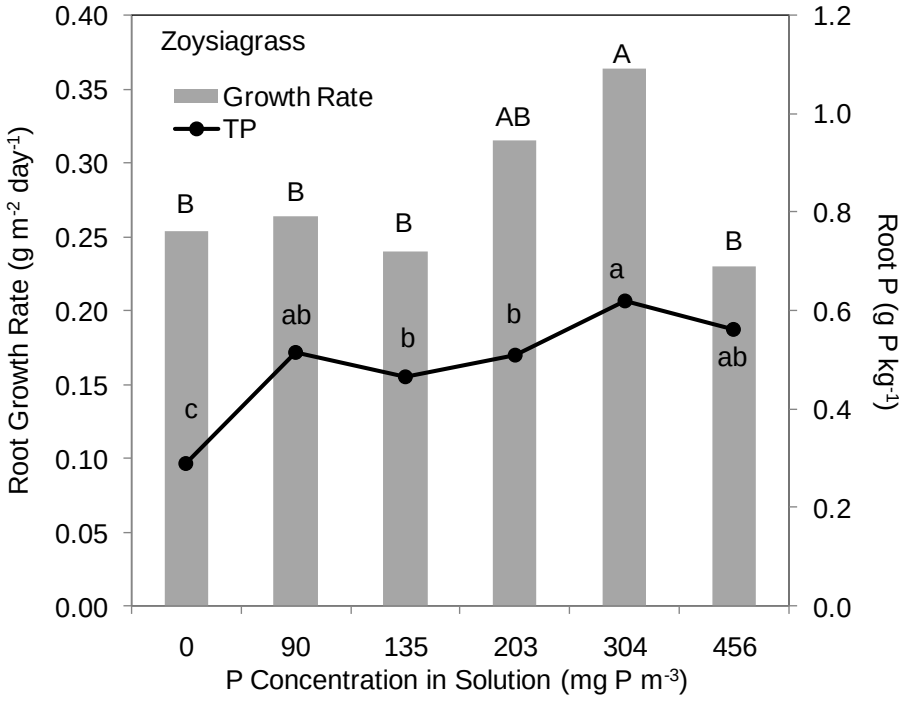
Turf species	P Rates	Sampling dates†							
		2008	2009						
		8/26	5/15	6/11	6/25	7/09	7/23	8/20	9/04	9/18
	mg P m^{-3}	---------- g P kg^{-1}‡ ----------								
EZ§	0	1.91c	0.58bc	0.61d	0.53e	0.54e	0.51f	0.39f	0.43f	0.28f
	90	1.97b	0.73a	0.73cd	0.71d	0.78d	0.71e	0.72e	0.76e	0.63e
	135	1.69d	0.69ab	0.78bc	0.84c	0.94c	0.85d	0.90d	1.0d	0.86d
	203	2.09a	0.65ab	0.89bc	0.98b	1.01c	1.03c	1.07c	1.20c	1.15c
	304	1.91c	0.50c	0.93b	1.02b	1.10b	1.17b	1.35b	1.48b	1.43b
	456	1.91c	0.71a	1.25a	1.20a	1.43a	1.47a	1.78a	1.80a	1.79a
	CV(%)	6.80	14.27	14.06	7.31	6.99	9.58	7.28	6.14	7.28
SA¶	0	3.17e	0.22c	0.43d	0.45d	0.58f	0.61f	0.58f	0.66e	0.58e
	90	3.44b	0.25bc	0.56cd	0.64c	0.83e	0.82e	0.84e	0.93d	0.87d
	135	3.31d	0.33a	0.68c	0.72c	1.02d	1.00d	1.00d	0.95d	1.07cd
	203	3.66a	0.31ab	0.99b	0.97b	1.19c	1.26c	1.30c	1.36c	1.34bc
	304	3.42c	0.31a	0.91b	0.92b	1.35b	1.44b	1.57b	1.58b	1.58ab
	456	3.42c	0.23c	1.21a	1.19a	1.58a	1.82a	1.78a	1.76a	1.81a
	CV(%)	4.80	15.55	16.73	9.52	10.59	3.88	5.54	5.77	9.45

†Sampling dates within a given year are indicated by the month followed by the day.

‡Data values within a given column and turfgrass species followed by the same letter are not significantly different at p=0.05 by single degree of freedom contrast analysis.

§EZ= Empire zoysiagrass.

¶SA= Floratam St. Augustinegrass.



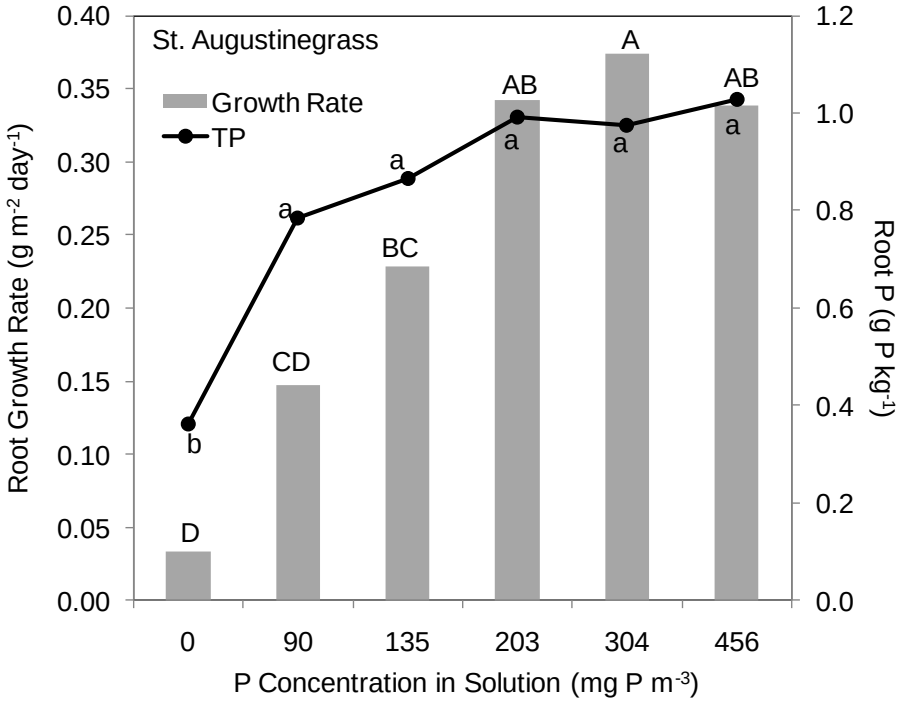


Fig. 1. Root growth rate and P concentration in root tissue relative to solution Pconcentration. Columns or filled circles along a line labeled with the same letter are not significantly different at p = 0.05 by contrasts analysis. Capital letters indicate statistical differences in root growth rate among treatments. Lower case letters indicate statistical differences in root tissue P among treatments.

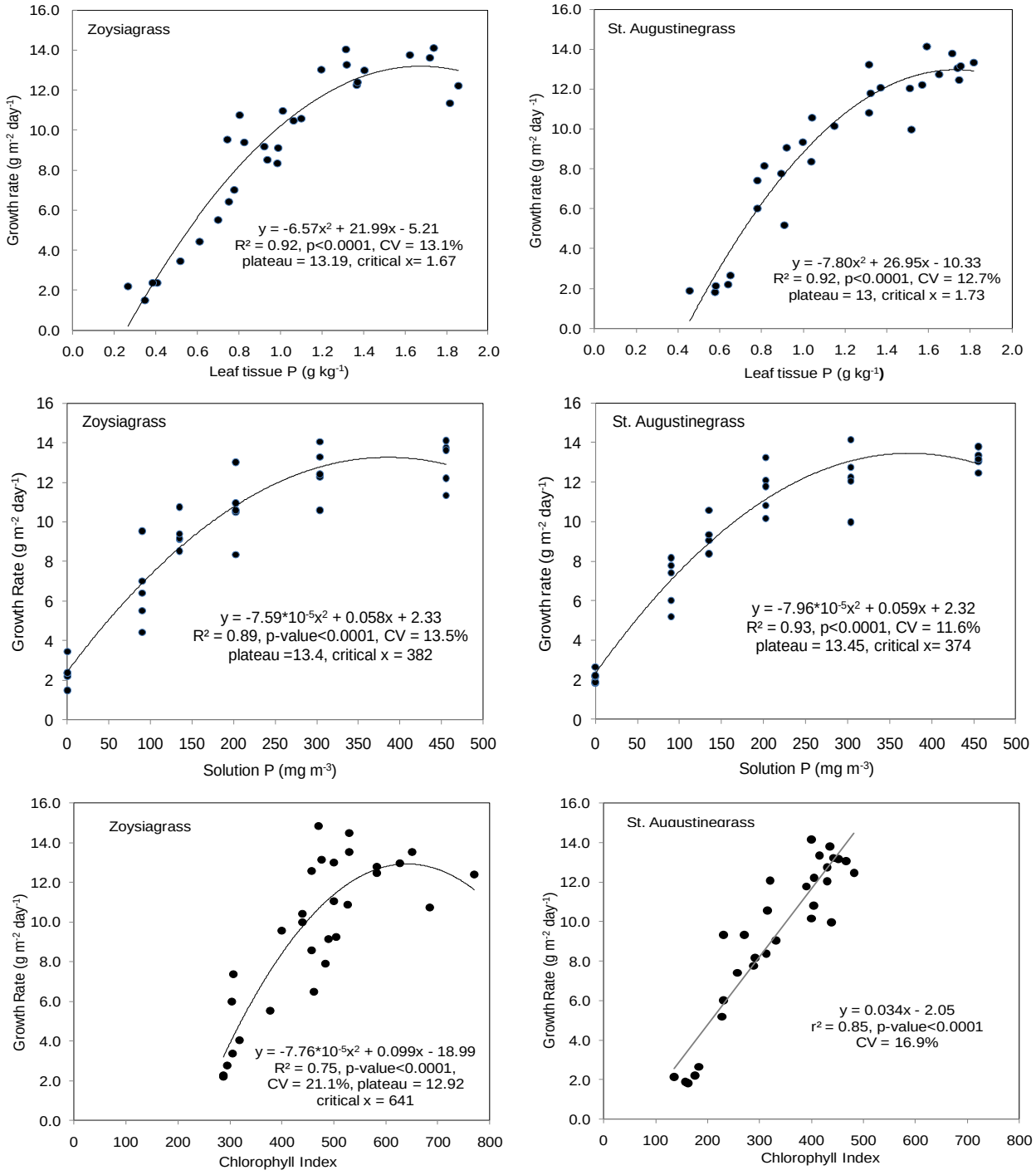


Fig. 2. Aboveground tissue growth rate relative to leaf tissue P concentration, nutrient solution P concentration and chlorophyll index.

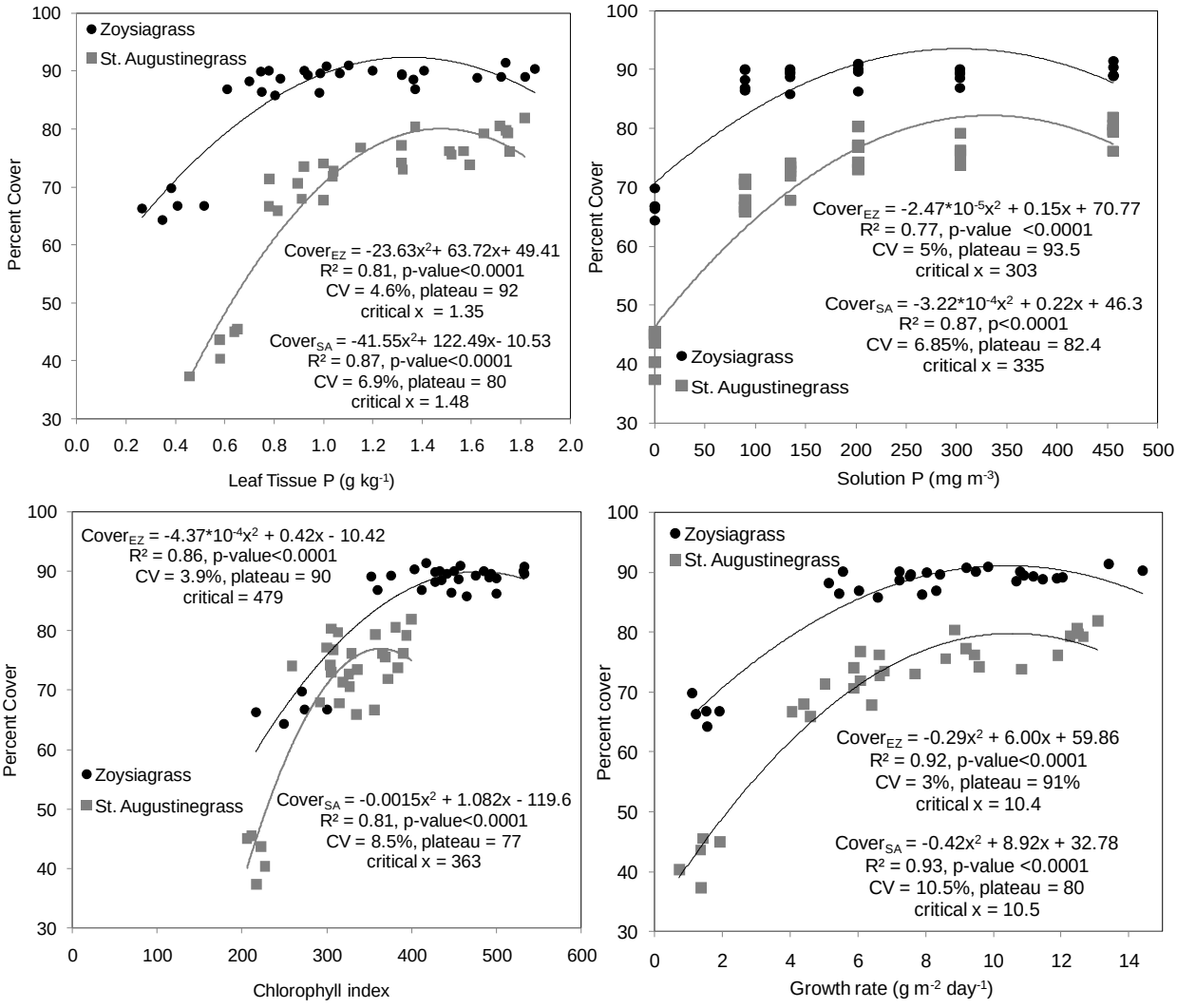
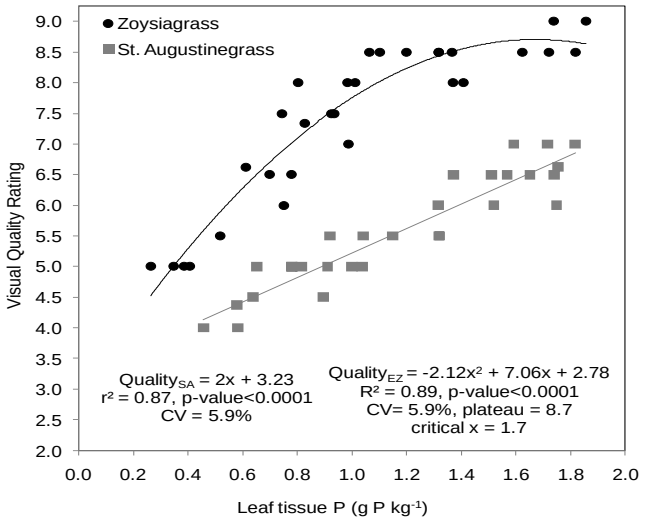
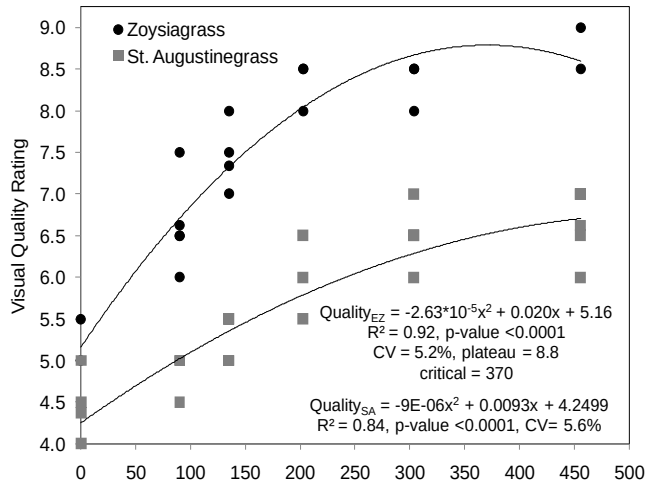


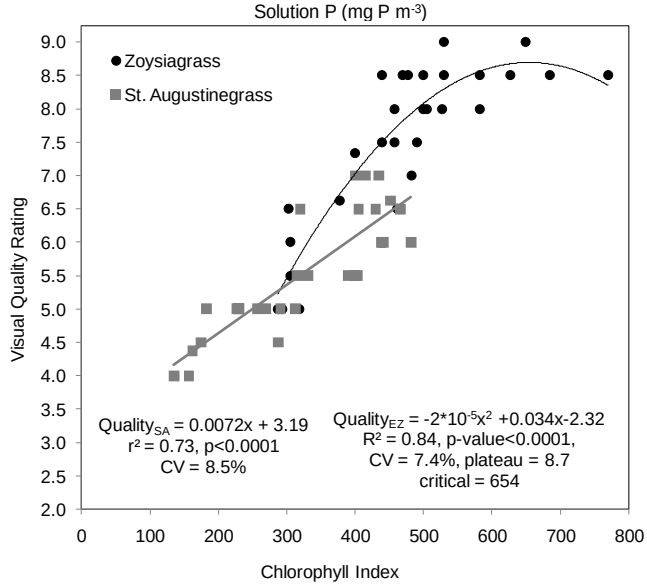
Fig. 3. Percent green turf cover relative to leaf tissue P concentration, solution phosphorus concentration, chlorophyll index, and leaf growth rate.



1



2



3

4 Fig. 4. Turf visual quality relative to leaf tissue P concentration, solution P concentration and
5 chlorophyll index.

REFERENCES

Andersen, J.M. 1976. An ignition method for determination of total phosphorus in lake sediments. Water Res.10: 329-331.

Andrew, C.S. and M.F. Robins. 1971. The effect of phosphorus on the growth, chemical composition, and critical phosphorus percentages of some tropical pasture grasses. Aust. J. Agr. Res. 22:693-706.

Burton G.W., R.N. Gates, and G.J. Gascho. 1997. Response of Pensacola bahiagrass to rates of nitrogen, phosphorus and potassium fertilizers. Soil and Crop Sci. Soc. Florida Proc. 56:31-35.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications. 8(3):559-568.

Carrow, R.N., D.V. Waddington, P.E. Rieke. 2001. Turfgrass soil fertility and chemical problems: assessment and management. Ann Arbor Press, Chelsea, MI, USA.

Cisar, J.L., G.H. Snyder, and G.S. Swanson. 1992. Nitrogen, phosphorus and potassium fertilization for histosol-grown St. Augustinegrass sod. Agron. J. 84:475-479.

Correll, D.L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual.27:261-266.

Foy, R. H. 2005. The return of the phosphorus paradigm: agricultural phosphorus and Eutrophication. p. 911-9.39. *In*: J.T. Sims and A.N. Sharrpley (eds.). Phosphorus: Agriculture and the environment. Agronomy Monograph no. 46, Madison, WI.

Guertal, E.A. 2007. Phosphorus leaching from sand-based putting greens. USGA Turfgrass Environ. Res. Online 6:1-6.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, W. L. Nelson. 1999. Soil fertility an fertilizers:An introduction to nutrient management. 6th ed. Prentice-Hall Inc., Upper Saddle River, NJ.

Hoagland, D.R., D.I. Arnon. 1950. The water culture methods for growing plants without soil. Circular 347, Cal. Agri. Exp. Sta., Univ. of California, CA.

Johnson, P.G., R.T. Koenig, K.L. Kopp. 2003. Nitrogen, phosphorus and potassium responses and requirements in calcareous sand greens. Agron. J. 95:697-702.

Juska, F.V. 1959. Response of Meyer zoysia to lime and fertilizer treatments. Agro. J. 51:81-83.

Karcher, D. E., and M. D. Richardson. 2005. Batch analysis of digital images to evaluate turf characteristics. Crop Sci. 45:1536-1539.

Liu, M., J.B. Sartain, L.E. Trenholm and P. Nkedi-Kizza. 2006. St. Augustinegrass phosphorus requirements using hydroponic culture. Soil Crop Sci. Soc. of FL Proc. 65:15-20.

Liu, M., J.B. Sartain, L.E. Trenholm and G.L. Miller. 2008. Phosphorus requirements of St. Augustinegrass grown in sandy soils. Crop Sci. 48:1178-1186.

Lukina, E.V., M.L. Stone, and W.R. Raun. 1999. Estimating vegetation coverage in wheat using digital image analysis. J. of Plant Nutrition. 22(2):341-350.

Ma, B.L., M.J. Morrison, and L. M. Dwyer. 1996. Canopy reflectance and field greenness to assess nitrogen fertilization and yield of maize. Agron. J. 88:915-920.

Madison, J.H., A.H. Andersen. 1963. A chlorophyll index to measure turfgrass response. Agron. J. 55:461-464.

Mangiafico, S.S., F. Guillard. 2005. Turfgrass reflectance measurements, chlorophyll and soil nitrate desorbed from anion exchange membranes. Crop Sci.45:259-265.

Mengel, K., and E. Kirkby. 2001. Principles of plant nutrition. 5th ed. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Menn, W.G., G.G. McBee. 1970. A study of certain nutritional requirements for Tifgreen bermudagrass (Cynodon dactylon x C. transvaalensis L.) utilizing a hydroponic system.

O'Dell, J. W. 1993. Determination of phosphorus by semi-automated colorimetry. Environmental Monitoring Systems Laboratory, Office of Research and Development. U.S. Environmental Protection Agency, Cincinnati, OH, USA.

Purcell, L.C. 2000. Soybean canopy coverage and light interception measurements using digital image analyses. Crop Sci. 40:834-837.

Richardson, M.D., D.E. Karcher and L.C. Purcell. 2001. Quantifying Turfgrass Cover Using Digital Image Analysis. Crop Sci. 41:1884-1888.

Rodriguez, I.R., G.L. Miller. 2000. Using a chlorophyll meter to determine the chlorophyll concentration, nitrogen concentration, and visual quality of St. Augustinegrass. HortScience. 35:751-754.

Rodriguez, I.R., G.L. Miller, B. McCarty. 2000. Sprigged bermudagrass needs ample phosphorus at grow-in. Golf course management. 68(6):59-62.

SAS Institute Inc. 2009. *SAS/STAT ® 9.2 User's Guide, Second Edition*. Cary, NC. SAS Institute Inc.

Satterthwaite, L.N., A.W. Hodges, J.J. Haydu, and J.L. Cisar. 2009. An agronomic and economic profile of Florida's sod industry in 2007. Univ. of Florida, IFAS, Florida Agric. Exp. Stn. , Florida Coop. Ext. Serv., Gainesville, FL.

Shuman, L.M. 2002. Nutrient leaching and runoff from golf courses. USGA Turf. And Environ. Res. Online. 1(17):1-9.

Skogley, C. R., and C.D. Sawyer. 1992. Field research. p.589-614. *In*: D.V. Waddington, R.N. Carrow, and R.C. Shearman (eds.). Turfgrass. Agron. Monogr. 32. ASA, CSSA, and SSSA, Madison, WI.

Soldat, D.J., and M. Petrovic. 2008. The fate and transport of phosphorus in turfgrass ecosystems. Crop Sci.48:2051-2065.

Spectrum Technologies Inc. 2009. 2950 Field Scout CM 1000 Chlorophyll Meter Manual. Plainfield, Illinois, USA.

Trenholm, L.E., R.N. Carrow, and R.R. Duncan. 1999. Relationship of multispectral data to qualitative data in turfgrass research. Crop Sci. 39:763-769.

Trenholm, L. E., and J. B. Unruh. 2005. The Florida lawn handbook: Best management practices for your home lawn in Florida. 3rd ed. University Press of Florida, Gainesville, FL.