PHOSPHORUS REQUIREMENT OF ST. AUGUSTINEGRASS

By

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To my wife Ma, Kehong, my father, Liu, Dinghong and my mother, He, Wanmei

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PHOSPHORUS REQUIREMENT OF ST. AUGUSTINEGRASS

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St. Augustinegrass [Stenotaphrum secondatum (Walt.) Kuntze] is widely used for Florida lawn grass. At present phosphorus (P) fertilization of Florida lawn grasses is based on soil tests which were designed for agronomic crops in a production culture. Little information exits relative to the exact P requirement of St. Augustinegrass. The objective of this research was to determine the critical P requirement of St. Augustinegrass. Four individual studies were conducted in a glasshouse including one solution culture study and three soil studies. Data collected in the solution culture study included visual quality rating, top growth rate, tissue P concentration. From the solution culture study, the critical solution P concentration and critical minimum tissue P concentration were determined to be 111 ppb and 1.6 g kg^{-1}, respectively. Data collected in soil studies included visual quality rating, top growth rate, tissue P concentration, soil test P concentrations, and leachate volume and soluble reactive P concentration. From the soil studies, the minimum P application rate to achieve the maximum growth rate was 0.31 g P_2O_5 m^{-2} 4-wk^{-1}; the critical minimum tissue P concentration were determined to be 1.8 g kg^{-1}. Mehlich-1 P, Fe Oxide Strip P, and WEP were highly correlated to each other and they were also highly correlated to tissue P concentration and top growth rate. Mehlich-1 was the best soil P extractant for St. Augustinegrass. The critical soil Mehlich-1 P

levels were in the range from 5 to 9 mg kg^{-1} depending on soil properties. Most of the applied concentrated superphosphate did not leach below the top 2 cm of soil. Approximately 1% of P applied leached in the 10 cm of soil profile. Larger quantity and higher concentration of P leached in the first leaching event. Application of 0.31 g P_2O_5 m^{-2} 4-wk^{-1} did not result in either a larger leached P quantity or a higher concentration. Based upon these research findings, 0.31 g P_2O_5 m^{-2} 4-wk^{-1} is recommended for St. Augustinegrass only if the soil Melich-1 P concentration is below 10 mg kg^{-1}. Otherwise, no P application would be recommended. Multiple applications with small quantity each time is suggested and do not apply P fertilizer before a rain event.

CHAPTER 1
INTRODUCTION

In the recent past, more attention has been directed towards phosphorus (P) fertilization of Florida lawn grasses, because P is recognized as an element of impairment of water bodies and streams, which is called eutrophicaiton. Eutrophication of surface waters, the proliferation of aquatic plants, is caused by a surplus of available nutrients (such as P and N). Eutrophication can cause a decrease in dissolved oxygen in waterways, a situation that can kill fish. Compared with the other major nutrients, phosphorus (P) is by far the least mobile and available to plants in most soil conditions. The poor mobility of soil inorganic phosphorus is due to the strong reactivity of phosphate ions relative to numerous soil components and to the consequent strong retention of most soil phosphorus onto those components. However, a typical Florida soil is sandy and acidic, and the potential for P leaching exists. Ballard and Fiskell (1974) reported that most of the sandy soils of the Southeastern Coastal Plains have a very small retention capacity for water soluble P against leaching, but that the surface horizons of Spodosols had the lowest retention capacities. In a lysimeter study, Neller (1946) reported that in 4 months 72.4 cm of rainfall leached more than 70% of applied superphosphate-P from the surface of 20 cm of a Leon fine sand. Therefore, P applied to Florida lawn grasses have potential to cause eutrophication if not managed properly. At present P fertilization of Florida lawn grasses is based on soil tests with were basically designed for agronomic crops in a production culture. Little information exists relative to the exact P requirement of Florida lawn grasses and fertilization levels required to produce the required levels in the soil. The objectives for this study are to identify the critical P tissue P concentration of the St. Augustinegrass using solution culture techniques; to determine the minimum P fertilization level on four types of soils (three with low in Mehlich-1 P and one with medium level of Mehlich-1 P) required to achieve the optimum growth; to select the best soil P

test procedure for recommendation on St. Augustinegrass; and to identify the critical minimum soil test P level to achieve the optimum growth.

CHAPTER 2
LITERATURE REVIEW

Phosphorus in the Soil-Plant Environment

Phosphorus is a macro nutrient used by plant. The most essential function of P in plants is in energy storage and transfer. Phosphorus is also an important structural component of nucleic acids, coenzymes, nucleotides, phosphoproteins, phospholipids, and sugar phosphates. Plant tissue P concentration ranges between 1 to 5 g kg^{-1}. Plants absorb either $H_2PO_4^-$ or HPO_4^{2-} orthophosphate ions (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 the 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). In order to ensure adequate P availability to plants and limit the environmental impact of P fertilization, one must thoroughly understand the P-cycle (Figure 2-1) and the dynamics of P transformations in soils.

Phosphorus Reactions in Soil

Phosphorus ions have a strong tendency to form ion pairs or complex species with several metal cations, most frequently with Ca and Mg in alkaline soils, and with Fe and Al in acid soils (Lindsay, 1979). Ruiz (1992) reported that 9 and 20% of soluble P occurred as Mg-P and Ca-P complexes for a hydroxyapatite in equilibrium with a simplified nutrient solution (NH_4NO_3 2 mM, KNO_3 3.5 mM, and $MgSO_4$ 0.5 mM) at pH values of 7 and 8.5, respectively. Phosphorus ions also readily precipitate with metal cations to form a range of P minerals in case of external

concentrations. In acidic conditions P ions will precipitate as Fe and Al phosphates such as strengite, vivianite, variscite and various minerals of the plumbogummite group (Norrish and Rosser, 1983; Lindsay et al., 1989). With pH increasing to neutral or alkaline conditions, P ions will precipitate as Ca phosphates such as octacalcium or dicalcium phosphates, hydroxylapatite and eventually least soluble apatites (Lindsay et al., 1989). P availability in most soils is at a maximum near pH 6.5.

Many soil physical and chemical properties influence the P solubility and adsorption reactions in soils. Consequently, these soil properties also affect solution P concentration, P availability to plants, and recovery of P fertilizer by crops. Sanchez and Uehara (1980) reported the influence of clay mineralogy on P adsorption. For three soil orders with >70% clay content, they found that the P adsorption occurred in the order: Mollisol soils composed mainly of montmorillonite < Oxisoil soils containing some Fe/Al oxides < the Andept soils composed principally of Fe/Al oxides and other minerals. Soils containing large quantities of clay will fix more P than soils with low clay content. Coleman et al. (1960) reported a strong positive linear relationship between exchangeable Al and P adsorption.

Organic Soil P

Organic soil P represents about 50% of the total P in soil and varies between 15 and 80% in most soils (Havlin et al., 1999). Havlin et al. (1999) also reported that soil organic P decreases with depth and the distribution with depth varies among soils. The average C/N/P/S ratio in soils is 140:10:1.3:1.3 (Havlin et al., 1999). Many of the organic P compounds in soils have not been characterized. Most organic P compounds are esters of orthophosphoric acid and have been identified primarily as inositol phosphates with approximate proportion of 10-50%, Phospholipids with proportion of 1-5% and nucleic acids with proportion of 0.2-2.5% (Havlin et al., 1999). In general, P mineralization is similar to N. Dormaar (1972) reported that organic P

content decreases with crop growth and increases again after harvest, which suggests P mineralization and immobilization. Tiessen et al. (1982) reported that organic P decreased an average of 21% after 60 and 70 years of cultivation. Sharpley (1985) reported that with an increase of total organic P content, the organic P mineralization rate increased. Tabatabai and Dick (1979) found that P mineralization increases with increasing total organic C. The C/P ratio of the decomposing residues regulates the predominance of P mineralization over immobilization as suggested by the following guidelines. Net mineralization of organic P occurs in case the C/P ratio is less than 200 and net immobilization of inorganic P would occur for a >300 C/P ratio.

Leached P in Turfgrass Environment

Phosphorus is an essential macronutrient required by turfgrass for proper growth and function. Accordingly, P is often included in fertilizer regime used to maintain aesthetic lawns. Although P enters into many inorganic forms in natural setting, which renders it sparingly soluble by precipitation and adsorption in most cases and not prone to leaching, a typical Florida soil is sandy and acidic, and the potential for P leaching exists. Many of Florida's soils have low P-retention capacities, which allow significant P leaching. Additionally, shallow groundwater intercepted by drains allows leached P to join surface water bodies. From 20 to 80% of P and other fertilizers which were applied to Florida sandy soil may be leached (Champbell et al., 1985; Sims et al., 1998). Shuman (2001) investigated P leaching from a simulated USGA putting green in an environmentally controlled greenhouse and reported 27% of applied P was lost via leaching.

Studies addressing N leaching from turfgrass environment are quite extensive (Snyder et al., 1980; Broschat, 1995; Erickson et al., 2001). Relatively few studies have addressed the P leaching under turfgrass environment. Erickson et al. (2005) examined fertilizer P leaching loss from contrasting residential landscape models (St. Augustinegrass vs. a mixed-species landscape) established on a sandy soil. They reported that during the 45 month study, cumulative mean P

leached was 23 kg ha^{-1} from approximate 1400 kg ha^{-1} application on the St. Augustinegrass model. Leaching losses were high during establishment and following intense precipitation. Leaching losses of P were high enough to raise concern over ecological impacts on neighboring hydrologically linked systems. Chung et al. (1999) evaluated the influence of a number of different P sources in a glasshouse study simulating the USGA putting green root-zone mixes on bermuda (*Cynodon dactylon* (L.) Pers. *C. transvaalensis* Burtt Davy) growth, plant uptake and leaching characteristics. They reported differences in P leaching characteristics among the P sources, with monopotassium phosphate contributing the largest quantity of P to the leachate, accounting for approximately 28% P applied, and concentrated superphosphate (CSP) the least, accounting for 13% of P applied. Brown and Sartain (1999) studied the P retention in United States Golf Association Greens by looking at the influence of sand type (clay coated vs. uncoated), amendment sources (peat and iron humate), and P fertilizer materials (MKP, 0-20-20, and CSP). They reported that more P leached during establishment. Coated sand retained more Mehlich-1 extractable P, which resulted in more P uptake and less P leaching. Iron humate reduced leachate P and experiment units receiving CSP leached least P. Snyder et al. (2000) investigated coated sands for use in putting green construction and concluded that naturally-coated sand retained more P than uncoated and artificially-coated sand with approximately 1% leached for naturally-coated sand.

Management Practices to Reduce P Leaching

Different management practices have been proposed to minimize P leaching in sandy soils. In recent years, water treatment residuals have been studied extensively to improve the P holding capacity of sandy soils. O'Connor et al. (2002) evaluated WRTs P retention capacities and found that all three WRTs tested could reduce P solubility by either adsorption, precipitation, or both mechanisms and the Al-WTR had an especially large P-sorption capacity of at least 5000 mg P

kg^{-1}. Decreasing P fertilizer rates or application of calcite or dolomitic limestone to increase soil adsorption capacity are the traditional ways for reducing P leaching (Sims et al., 1998). However, both procedures may lead to insufficient P availability to plants because liming promotes transformation of plant-available P into unavailable forms (Lindsay, 1979). Silicon fertilizers have a high adsorption capacity and positively influence soil physical properties. As a result of P adsorption onto a surface of Si fertilizer, P leaching is reduced. At the same time, Si fertilizers can induce transformation of slightly soluble phosphates into plant available forms (Matichkov and Ammosova, 1996). Therefore, Si fertilizers can improve P nutrition in plants and keep P in the upper soil layers. Matichenkov et al. (2001) found that Si-rich substances or Si fertilizers increased bahiagrass biomass and reduced P leaching by 40 to 70%.

Conventional Soil and Tissue P Tests

Soil P Extractants

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. Soil P test extractants can be placed into various categories related to the chemical nature of the extracting solutions. A list of the commonly used soil test extractants is given in Table 2-1.

Extractants Troug and Mehlich-I contain dilute concentrations of strong acids normally with a pH of 2 to 3. This provides sufficient H ion activity to dissolve the Ca-P and some of the Al-P and Fe-P as well. Mehlich III, Bray I and Bray II contain both diluted strong acids and a complexing agent, fluoride ion. Fluoride ions are very effective in complexing Al ions from Al-P and also precipitate Ca ions to release P form Ca-P into solution. With the double effects of P

extraction mechanism Mehlich-III, Bray-I and II tend to extract more P from the same soils than Mehlich-I and Troug would. On coarse textured Georgia Coastal Plain soils, Gascho et al. (1990) found that Mehlich-III extracts about 1.46 times more P than Mehlich-I. Also, on finer textured soils Mehlich-III extractant removes about 1.6 times more P than Mehlich-I. Olsen-P extractant is so called buffered alkaline solution containing 0.5N $NaHCO_3$ with pH 8.5, which originally was developed for calcareous soils. The HCO_3^- is quite effective in replacing adsorbed P. Because of high pH Olsen-P extractant is also very effective in extracting P from Al-P and Fe-P due to the hydrolysis of the Al and Fe. The extractant citric acid, Egner and Morgan, consist of diluted weak acids, which were developed based upon the idea of mimicking the root environment. The organic anions associated with the weak acids tend to affect the extraction in two ways. The organic anions form complexes with Ca, Al or Fe ions to release P and can also replace adsorbed P and prevent its readsorption. Modified Morgan extractant was modified from Morgan extractant by substituting NH_4 for Na and adding NH_4F to provide a 0.03 N F solution. NH_4 is more effective in removing K from clay soils than is Na. NH_4F would give a measure of a greater portion of P reserve by forming Al-F or Fe-F complexes. FeO strip P test is the so-called chemical sink-based test, which has been proposed to rely on P sorption–desorption reactions instead of dissolving soil P with chemicals. It extracts P using Fe-oxide impregnated filter paper strips or discs (Chardon et al, 1996).

Suitability of Different Extracting Procedures

The suitability of the extracting methods can be evaluated by correlating the P extracted with plant growth parameters such as yield, P uptake and P concentration (Fitts and Nelson, 1956). The Olsen and Bray I methods are quite satisfactory across a wide range of soil conditions and the Mehlich I appeared to be very good when used for soils with a pH of 7 or less (Fitts, 1956). The soil testing laboratory at the University of Florida is currently using the Mehlich-I

procedure. The Egner method was as effective as Olsen and Bray-I methods while the Morgan method is least satisfactory across a wide range of soils (Van Diest, 1963). In a study that related turfgrass growth response to extractable soil P concentration in sand greens, Guillard and Dest (2003) reported that extractable P was highly correlated among Mehlich-I, Bray-I and modified-Morgan procedures with r value of around 0.9. Mehlich-I and Bray-I extractable P extracted four to six times more P than modified Morgan. Extractable P with Bray-I P was 1.3 times greater than Mehlich-I extractable P. A better correlation was observed between Bray P and Mehlich-I P than with modified Morgan P.

Soil P Extracting Procedures and Geographical Regions

The compounds that control the availability of P differ with soil conditions in different geographical regions of the country and different extractants have been developed and used for these situations. For example, P chemistry of soils in the southeast primarily involves factors affecting the availability of aluminum and iron phosphates. Therefore, most commonly used extractants in these regions are the Mehlich I and the Mehlich III. The Morgan extractant, which is used by some states in the northeast and Pacific northwest and contains acetic acid, is a buffered weak acid extractant. Both of the Mehlich solutions extract more P from soils than the Morgan extractant. The Mehlich III extractant removes about 10 times more P from soils than the weak acid-based Morgan extractant (Wolf and Beegle, 1995). The extractant used predominantly in the Midwest is the Bray-Kurtz, commonly referred to as Bray I. The extraction of P by this procedure is based upon the solubilization effect of the H^+ on soil P and the ability of the F to lower the activity of A1 and to a lesser extent that of Ca and Fe by forming complexes in the extraction system. Clay soils with moderately high base saturation or silty clay loam soils that are calcareous or have a very high base saturation will lessen the ability of the extractant to solubilize P. Consequently, the method should normally be limited to soils with pH_w (soil pH

determined in water) values less than 6.8 when the texture is silty clay loam or finer. Calcareous soils, or high pH, fine textured soils may be tested by this method provided the soil:solution ratio is changed from 1:10 to 1:50. However, it should be noted that the Olsen extractant is used most extensively for calcareous soils (Anonymous, 1992, Knudsen and Beegle, 1988). The Olsen extractant is quite effective for soils with medium to high CEC, high percent base saturation, moderate to high amounts of calcium phosphates, and containing free calcium carbonates (Thomas and Peaslee, 1973). It is used extensively in states such as Arizona, California, Utah, Wyoming, and Oregon. Research also indicates that the procedure works reasonably well on moderately acid soils. However, not many laboratories testing moderately acid soils use the procedure. The fact that it is not used more widely on these soils is probably due to the lack of correlation data.

Tissue P test

Plant tissue analysis is an indicator of attaining or maintaining maximum yield or quality. Therefore, the good correlation between the concentration of P in plant tissue and in the soil as well as between the concentration in plant tissue and yield, plant growth or quality normally exists. Ballard and Pritchett (1975) reported that the relationship between the concentrations of P extracted from the soil by different extractants correlated highly with the concentration of P in the tissue of pine seedlings.

Response of Turfgrass to P Fertilizers and Fertilizer Recommendations

Phosphorus Toxicity Trial

Accumulations of P in soils growing turf, citrus, vegetable crops and field crops are common when heavy application of fertilizers containing a high proportion of P are usually applied frequently. Since only a portion of P added in fertilizers is recovered by plants, the continuous use of P fertilizers on turfgrass would be expected to raise soil P level well above the

optimum level. In most states, soils contain substantial portion of clay and P leaches very little. Scientists question whether or not these high levels are detrimental to plant growth. Juska et al. (1965) looked at the effects of P on the development of Red Fescue (*Festuca rubra ssp. commutata*), Merion, and Common Kentucky Bluegrass (*Poa pratensis*). The P application rates were: 0, 244, 488, 734, 978, 1222, 1466 and 1710 kg ha^{-1}. The largest increase in weight of both tops and roots of Merion and common Kentucky bluegrass resulted from the first increment of P. Differences among remaining increments were small. It is conceivable that P application as high as 1710 kg ha^{-1} did not depress top growth and P application rate of 244 kg ha^{-1} supplied sufficient P already. These results suggest that grasses can tolerate very high levels of P and may require low rate of P application for optimum growth.

Phosphorus Requirements by Turfgrasses

Grasses exhibit marked species difference in response to P supply. Robinson et al. (1976) found no influence of P applications to a New Zealand browntop-New Zealand chewings fescue (*Festuca rubra var. commutate*) lawn mixture for verdure, root weights, or tiller numbers. Jones et al. (1970) grew Italian ryegrass (*Lolium multiflorum*), hardinggrass (*Phalaris tuberosa var. stenoptera*), tall fescue (*Festuca arundinace*), orchardgrass (*Dactylus glomerata*), and tall oatgrass (*Arrhenatherum elatius (L.) P. Beauv*.) with 0, 100, 200, 300, and 400 kg P ha^{-1}. Tall fescue, ryegrass, and tall oatgrass produced the highest yields without P, but tall fescue and ryegrass also showed the greatest response to P fertilization. Christians et al. (1979) investigated the N, P and K effects on quality and growth of Kentucky bluegrass and creeping bentgrass (*Agrostis palustris*) using solution culture. No response to P levels in solution was observed, which indicated that the requirements of these two species for P, under the conditions established, were met at or below the lowest P level of 2 mg L^{-1} in solution. Fry et al. (1989) conducted a field study over 8 years on a sand medium to determine creeping bentgrass quality response to P.

They found that creeping bentgrass fertilized at 60 or 132 kg P ha^{-1} yr^{-1} was similar in quality. In calcareous sand greens Johnson et al. (2003) found that creeping bentgrass plots receiving 27.5 kg P ha^{-1} yr^{-1} or higher rates attained the maximum quality. Allen et al. (1977) established Pensacola bahiagrass (*Paspalum notatum*) on a Lexington silt loam that contained 34 mg kg^{-1} P in the surface 1.5 m soil. For 5 years they applied annually 224, 336 and 448 kg N ha^{-1}; 112, 224 and 336 kg P_2O_5 ha^{-1}; and 112, 224 and 336 kg K_2O ha^{-1} in a complete factorial experiment. Rates of 224 and 336 kg P_2O_5 ha^{-1} accounted for increases of only 1% and 2% forage above the 49 kg P_2O_5 ha^{-1} level, respectively. Maximum yield response of bahiagrass to P fertilizer in south Florida occurred on Arenic Haplaquods at 24 kg P ha^{-1} (Rechcigl et al., 1992). Another study on the bahiagrass fertility requirement in south Florida on soils with a spodic horizon called for13 kg P ha^{-1}, and only if >112kg N ha^{-1} is applied. If less than 60 kg N ha^{-1} is applied, no P is recommended (Sumner et al., 1991). Turner (1980) found little influence of P on the growth of perennial ryegrass (*Lolium perenne*), Kentucky bluegrass, or creeping red fescue, despite low soil P levels.

Robinson and Eilers (1996) obtained 90% of maximum ryegrass dry matter yield with 45 to 50 kg P ha^{-1} on a Tangi silt loam (Typic Fragiudult) at pH 6. Higher rates of P had little influence on yield but significantly increased P removed by the crop. This result was consistent with the study of irrigated annual ryegrass responses to N and P on calcareous soil by Lippke et al. (2006), in which they concluded that increments of growth responses to levels of fertilizer about 39 kg applied P ha^{-1} were relatively small. Watschke et al. (1977) looked at the effect of P application of 0, 85, 170, 340, and 680 kg P ha^{-1} on soil test and tissue analyses P. Phosphorus fertilization increased the Bray extractable P from 13 to 137 mg kg^{-1}. Treatments P1, through P5 gave P concentration of 3.2, 3.5, 3.6, 3.8, and 4.4 g kg^{-1}, respectively, with all differences being

significant except 3.5 and 3.6 g kg^{-1}. When soil test P was related to yield response, the correlation was slightly lower than those found for tissue P and yield, which was in agreement with Hall and Miller (1974) who also found that tissue P and yield were better correlated than soil test P and yield. Watschke et al. (1977) also investigated the zone of maximum root absorption for 'Merion' Kentucky bluegrass as affected by P application. Results indicated that P enhanced rooting, and the magnitude of absorption from the 1.3-cm depth exemplified the need for P near the soil surface for optimum turf establishment. Juska (1959) reported that adequate P was necessary for rapid establishment of zoysiagrass (*Zoysia spp*) on a soil extremely low in P. St. Augustinegrass growth was affected by P most during the first 8 weeks of establishment (Wood and Duble, 1976). On P-deficient soils, McVey (1967) reported a Kentucky bluegrass seedling growth response to extremely low rates of P applications. Long-term benefits from P application to the seedbed have also been observed by Turner et al. (1979). He reported that 6 years after establishment, spring greening was enhanced by the original seedbed P applications.

Critical Minimum Soil P Concentrations

The critical soil test level implies the P level above which little or no response to fertilizer P is obtained. Woodhouse (1969) and Jordan et al. (1966) reported that about 25 mg kg^{-1} of Mehlich-1 extracted soil P is adequate for coastal bermudagrass (*Cynodon dactylon*) in North Carolina and Alabama. Lunt et al. (1965) indicated that about 14 mg kg^{-1} of Olsen extractable P was adequate for common bermudagrass harvested frequently as turfgrass; Bruce and Bruce (1972) indicated that 17.5 mg kg^{-1} of P extractable with 0.005 M H_2SO_4 was necessary for high production of various tropical grasses. Vicente-Chandler et al. (1974) concluded that tropical species such as guineagrass (*Urochloa maxima*), napiergrass (*Pennisetum purpureum*), and stargrass (*Cynodon plectostachyus*) require fertilization with at least 73 kg P ha^{-1} annually when cut every 40 to 60 days. Annual ryegrass (*Lolium multiflorum Lam.)* response to applied P

ranged from 8300 to 8600 kg ha^{-1} as extractable soil P increased from 3 to 55 mg kg^{-1} (Hillard et al., 1992). Christians et al. (1981) did not find significant quality responses for creeping bentgrass on calcareous sand greens when initial Bray-1 extractable P concentrations were 12 mg kg^{-1}. Dest and Guillard (1987) reported that on a loam soil with modified Morgan extractable P at 10.7 mg kg^{-1}, quality responses of creeping bentgrass were not affected by P fertilization. Fry et al. (1989) reported that creeping bentgrass quality improved with addition of P on sand-based media putting greens only when extractable P was <5 mg kg^{-1}. Kuo (1993) reported that Olsen-extractable P concentrations at 95% of maximum clipping yields was from 2.8 to 4.8 mg kg^{-1} for the growth of annual bluegrass and creeping bentgrass (*Agrosti stolonifera L.*). In calcareous sand greens the critical Olsen-P level of 3.0 mg kg^{-1} was reported for the growth of creeping bentgrass (Johnson et al., 2003). For Pensacola bahiagrass on a virgin Clarendon loamy sand the critical Mehlich-1 P concentration was 3 mg kg^{-1}, which corresponded to 56 kg P_2O_5 ha^{-1} application (Burton et al., 1997). To locate the critical soil P concentration the plant growth rate or turf quality are most commonly used to relate to soil test levels. Guillard and Dest (2003) used a number of plant response variables including shoot counts, thatch thickness, relative clipping yields, quality ratings, P deficiency ratings, tissue P concentrations, and root weights, which resulted in different soil critical P concentrations. Selection of a particular critical extractable soil P concentration would depend on the quality or growth variable that is the most important to the individual manager. Among the three extractants, modified Morgan, Bray I and Mehlich I, critical extractable P concentrations for creeping bentgrass were lowest for the modified Morgan extractant (1.4 to 12.0 mg kg^{-1}) and greatest for the Mehlich I extractant (14.1 to 63.6 mg kg^{-1}).

The critical values are generally influenced by soil properties, such as texture and temperature. A lower amount of P is generally extracted from a clayey soil than from a sandy

soil (Woodruff and Kamprath, 1965). Rouse (1968) found that an application of 5 to 6 kg P ha^{-1} was required to raise Mehlich-I extractable P 1 kg ha^{-1} with sandy loam to clay loam textured Ultisols, but on clayey textured soils 12 kg P ha^{-1} were required to change the soil test values 1 kg ha^{-1}. Finn and Mack (1964) showed that both soil moisture and soil temperature affected P response of orchardgrass (*Dactylis glomerata*). Yields were higher at 75 than at 25% of the moisture-holding capacity at each level of P applied. Under 75% moisture-holding capacity level, at a 10 °C soil temperature, maximum yield of the S-143 cultivar occurred with 35 mg kg^{-1} of applied P; at 20 °C, yields were still increasing with 70 mg kg^{-1}.

Effects of P Application on Soil Test P Levels

When soil test P is below the critical level, the rate of fertilizer P recommended is sufficient to supply adequate P for the plant and to result in some buildup of available soil P when applied at the rate for several years. In trying to predict how much fertilizer P is needed to change the soil test P, information is needed about the P adsorption characteristic of the soil, which is related to soil texture, as well as the initial level of soil test P. In a Honeoye fine sandy loam soil, Peck et al. (1975) found that continuous applications of concentrated superphosphate over 10 yr for a total of 248 kg P ha^{-1} increased soil test P (Morgan's method) from 10 to 186 kg P ha^{-1}. An application of 4 kg P ha^{-1} was required to raise the Bray I extractable P of medium-textured Mollisols and Alfisols 1 kg ha^{-1} (Peck et al., 1971). Single applications of 22, 45, 90, and 180 kg P ha^{-1} raised the levels of Olsen P by 1, 2, 4, and 8 mg P kg^{-1} soil, respectively, on a glacial till soil after 16 yr of P fertilization (Halvorson and Black, 1985) . In a 29-yr study on Ultisols in Alabama, Cope (1981) found that 24 and 20 kg P ha^{-1} raised Mehlich-1 soil test P by 1 mg P kg^{-1} when P was applied at rates of 31 and 54 kg P ha^{-1} yr^{-1}, respectively. For a corn-soybean rotation on a Portsmouth fine sandy loam, annual rates of 19, 38, and 57 kg P ha^{-1} increased the soil test levels 7, 20 and 40 mg kg^{-1} P over a 7-year period (Kamprath, 1964). After

14 yr of annual application of P fertilizer in a Webster fine-loamy and a Canisteo fine-loamy soil located in north central Iowa, Webb et al. (1992) reported that annual P additions required to maintain Bray-1 P values increased from 16.8 to more than 33.6 kg P ha^{-1} with increases in the initial Bray-1 P value. In a Chicot sandy loam soil, an application of 14 kg P ha^{-1} of net added inorganic fertilizer P was required to increase soil Mehlich-3 P by 1.0 mg P kg^{-1} (Zhang et al., 1995). Cox (1994) showed that increases in Mehlich-3 with each unit of applied P were 0.7 units for soils with 10% clay, and it decreased exponentially to 0.2 units for soils with >50% clay. Results obtained from a study by Randall et al. (1997) in Minnesota, showed that every 1 mg P kg^{-1} increase in Bray-1 extractable P requires 35 and 20 kg P ha^{-1} in a Webster clay loam soil and 58 and 26 kg P ha^{-1} in a Aastad clay loam soil when fertilizer P was added at 24 and 49 kg P ha^{-1}, respectively. Many studies have shown that the amount of fertilizer P required for each unit increase of soil test P level varies with soil texture, soil test method employed, as well as the rate of fertilizer P applied.

Critical Tissue P Concentrations

The critical tissue P concentration is normally regarded as the minimum concentration associated with near maximum yield. The nutrient concentration in the plant at 90% of maximum growth has often been termed the critical concentration (Ulrich and Hills, 1967). It could be statistically determined from the shape of the yield response curve in relation to concentration of P in the selected tissue. Knowledge of the minimum P concentrations for plant growth has been used as a means to diagnose the P status of many plants (Hartt, 1955; Ulrich, 1952). Jones and Eck (1973) reported that the critical concentration of P in the sweet corn leaf tissue was from 0.27 to 0.29% and the corresponding equilibrium soil solution P concentration was about 0.12 to 0.13 mg L^{-1}. A similar highly positive linear correlation between percent P in the rice tissue and

soil solution P concentration was reported by Hossner et al. (1973). The critical tissue P concentration of 0.25% corresponds to the soil solution P of 0.1 mg L^{-1}.

Oertli (1963) reported that healthy bluegrass (Poa spp) and bermudagrass (Cynodon spp) contain 1.2 to 2.4 g kg^{-1} P, respectively. Tissue P-deficiency levels were found to be 0.5 to 0.8 g kg^{-1}, respectively, for bluegrass and bermudagrass. Martin and Matocha (1973) outlined approximate sufficient ranges for tissue P for cool-season forage grasses. For Kentucky bluegrass, values 1.8 g kg^{-1} were considered deficient, from 2.4 to 3.0 g kg^{-1} were critical, from 2.8 to 3.6 g kg^{-1} were adequate, and values 4.0 g kg^{-1} were considered high. For annual and perennial ryegrass values < 2.8 g kg^{-1} were deficient, from 2.8 to 3.4 g kg^{-1} were critical, from 3.6 to 4.4 g kg^{-1} were adequate, and > 5.0 g kg^{-1} were high. Jones (1980) suggested that in most situations concentrations below about 2.0 g kg^{-1} indicate a deficiency for plant growth while 3.0 to 3.5 g kg^{-1} is usually necessary for optimum yields. Wedin (1974) reported that P concentration in cool-season grasses range from about 1.4 to 5.0 g kg^{-1}. Johnson et al (2003) investigated the P requirement of creeping bentgrass on calcareous sand greens and found that tissue test of 4.0 g kg^{-1} was the optimum level for maximum quality. For warm-season grasses, the P concentration in plant tissue should be logically lower for the optimum yield compared with cool-season grasses because the higher growth rate dilutes the P concentration in plant tissue. Burton et al. (1997) reported that phosphorus concentration of the 1993 Pensacola bahiagrass forage receiving 56 kg P_2O_5 ha^{-1}, above which no significant yield increase occurred, averaged 1.5 g kg^{-1}. When P_2O_5 was increased to 112 kg ha^{-1}, forage P concentration increased to be 1.8 g kg^{-1}. The critical P concentrations in some subtropical and tropic grasses were shown in Table 2-2 (Kampraph, 1980).

Some factors may modify the critical P concentration of plants such as growth rate (Terman et al., 1972), plant tissue age (Jones et al., 1970) and cultivar effects (Terman et al., 1975), thus making the conclusion between tissue P concentration and yield difficult. Therefore, in many cases, the variability in the P concentration does not allow a high degree of accuracy in the prediction of the increments of plant growth or yield. Consequently, the critical concentration range of P in the plant is usually the criterion that is used in differentiating P deficiency from P sufficiency and the decision to simply apply P or not is usually made.

Interaction with other Nutrients

Phosphorus and N

Increased P absorption by plants is a common consequence of adding N fertilizers (Grunes, 1959). Templeton et al. (1969) conducted a study showing the effects of N on P response of orchardgrass. At each level of P applied, with increased N rate plant gained increased weight increased top growth, increased root growth, altered metabolism, and increased solubility of soil applied among three levels of N applications. In a study on response of bahiagrass to N, P and K on an Ultisol in North Florida, Rhoads et al. (1997) found that there were no interactions between N and P rates with respect to bahiagrass yield. However, there were significant interactions in 1996 between N and K rates and between P and K rates with respect to bahiagrass yield. Hylton et al. (1965) reported that for Italian ryegrass (*Lolium multiflorum Lam*), as the P supply increased from 0.16 to 0.64 mg per plant, the tissue NO_3-N concentration decreased from 13.2 g kg^{-1} with 0.16 mg of P per plant to a low of 7.6 g kg^{-1} with 0.64 mg. Engelstad and Allen (1971) found that root yields and root P contents were increased by N fertilizer, with ammonium being superior to nitrate. The addition of KNO_3 to the pellet reduced the P content of the tops. Sartain and Dudeck (1982) studied the effect of N fertilization on the P uptake of Tifway bermudagrass and overseeded ryegrass. Tissue P content was significantly reduced by each

increasing N rate on the ryegrass. The reduction in tissue P could possibly be attributed to a diluted effect caused by greater growth rate. Higher tissue N content was observed for Tifway bermudagrass by excluding P, which implied a possible nutrient uptake competition between NO_3-N and H_2PO_4-P. Sartain (personal communication) found that bermudagrass growth rate was reduced each of three years by the application of additional P. A reduction in N uptake was observed in conjunction with the reduction in growth rate. It was suggested that the competition effects of the NO_3-N and H_2PO_4-P anions may have been responsible for the observed reduction in N uptake and subsequent growth rate. Watschke et al. (1977) reported that clipping yield and rooting of Merion Kentucky bluegrass (*Poa pratensis L.*) were enhanced by the application of additional P. In case NH_4-N was applied during cool season, NH_4-N would be the major N form available for plant uptake because of reduced nitrification of the applied NH_4-N (Parker and Larson, 1962). The increased growth rate may possibly due to the fact that additional P enhanced N uptake for the cool season Kentucky bluegrass. Bluegrass tissue P levels were more than sufficient (3.2 g kg^{-1}) for all treatments, which indicate that the positive growth response to P was not related physiologically to P. With the exclusion of P fertilization the number of H_2PO_4-P anions would be reduced and the quantity of NH_4-N cations that can be accumulated would also be reduced, therefore, a yield reduction was expected.

Phosphorus and K, Ca and Mg

Enhanced P utilization due to K applications was observed for stargrass (Cynodon nlemfuensis Vanderyst var. nlemfuensis) by Pant et al. (2004). The applications of 10 and 93 kg ha^{-1} yr^{-1} of P and K, respectively, provided efficient P utilization. Phosphorus mass balance showed that stargrass removed maximum P (161%) of the applied P by uptake from soils. This may indicate that the supply of sufficient K appears to be crucial for efficient P utilization by forages, reducing potential adverse effects of P over-fertilization on water quality. When the

different P:K ratios were related to the total dry matter yield, the application of 10 and 93 kg ha^{-1} yr^{-1} of P and K, respectively, achieved almost 90% of the maximum total dry matter yield, which indicates that application of 10 kg P ha^{-1} yr^{-1} was critical for stargrass to achieve maximum dry matter yield. Greenwood and Hallsworth (1960) found no direct effect of P on Ca uptake, but found that earlier and more severe symptoms of Ca deficiency occurred where P levels were high. Mg has been ascribed the function of P 'carrier' in plants (Truog et al., 1947), based on a positive correlation between the Mg and P contents of plants or between fertilizer P efficiency and the supply of available Mg.

Phosphorus and Zn

Phosphorus and Zinc nutrition in plants have often been related. In P deficient plants additional P promoted plant growth resulting in depressed Zn concentrations in tissue and possible Zn deficiency conditions. In P sufficient plants additional P increase concentrations to toxic levels producing necrotic symptoms in old leaves and depressing new growth. Sartain (1992) investigated the influence of Zn and the interaction of P an Zn on the growth of bermudagrass. Application of Zn did not influence growth nor Zn uptake rate. Extractable soil Zn levels over 252 mg kg^{-1} did not affect bermudagrass growth nor quality. In effect, bermudagrass can tolerate high levels of soil extractable P and Zn without exhibiting toxicity effects.

Effect of N, P, K, and their Interactions on Water Use Efficiency

When water resources become limited, it is important for turfgrass manager to use many different cultural practices to reduce water loss through turfgrass evapotranspiration rate (ET). Nitrogen application enhanced the ET by promoting the top growth and total leaf area. Ebdon et al. (1999) investigated the interaction of N, P and K on ET rate of Kentucky bluegrass. The nature of the interaction between N, P, and K on Kentucky bluegrass water use can only in part

be explained by the interaction effects of N, P and K on shoot growth response. No relationship between clipping yield and ET rate at high P applications was found. They also discovered that at N and P levels that are routinely applied (147 kg N and 21.5 kg P ha^{-1} yr^{-1} and lower), increasing K levels minimized Kentucky bluegrass water use.

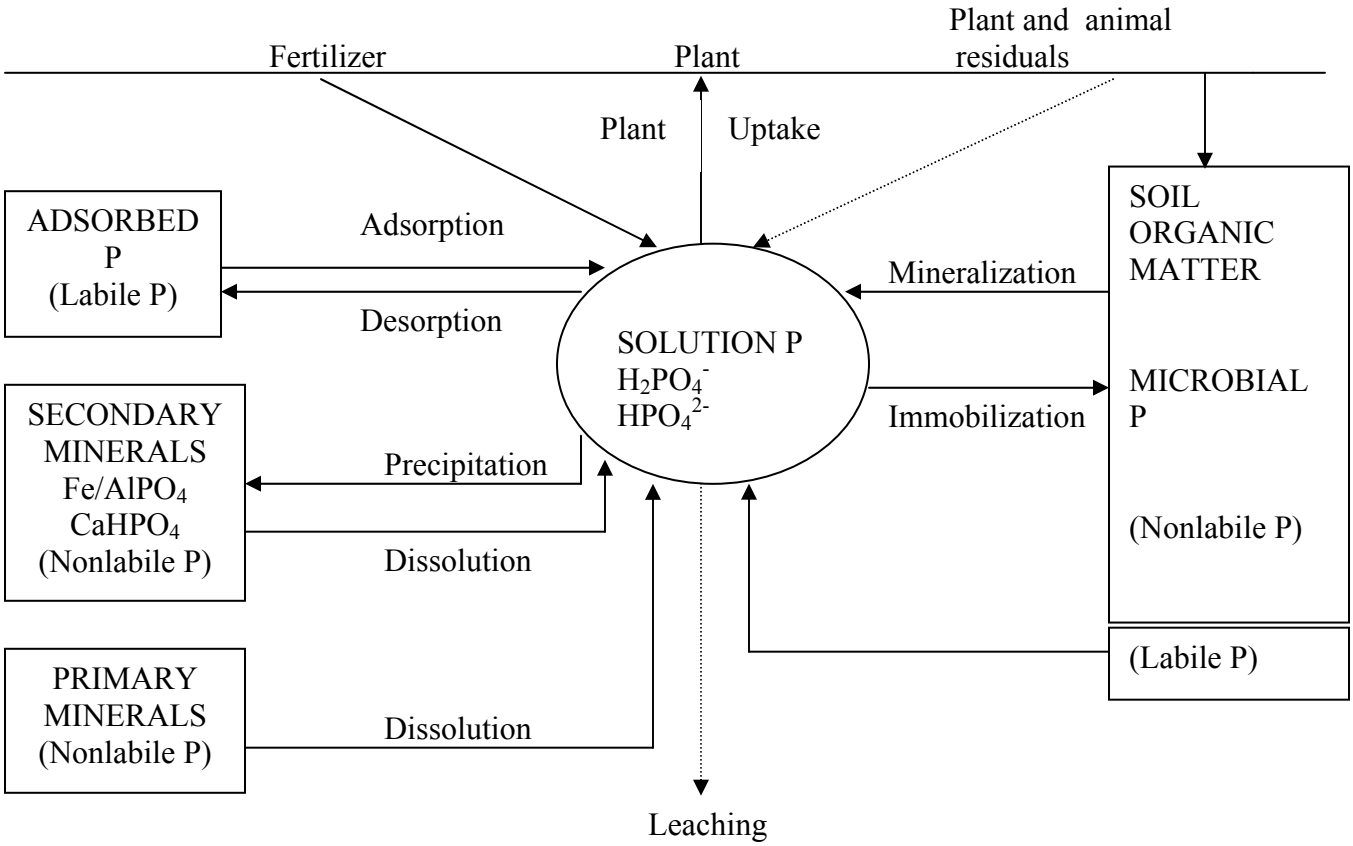

Figure 2-1. The P cycle in soil.

Table 2-1. Common soil test extractants used for available P.

Common name	Extractant	Soil/solution ratio	Reference
Troug	0.002N H_2SO_4 buffered at pH 3 with $(NH_4)_2SO_4$	1:100	Troug (1930)
Mehlich -I	0.05N HCl + 0.025N H_2SO_4	1:4	Mehlich (1953)
Mehlich-III	0.2N CH_3COOH + 0.25N NH_4NO_3 + 0.013N HNO_3 + 0.015N NH_4F + 0.001M EDTA	1:10	Mehlich (1984)
Bray-I	0.025N HCl + 0.03N NH_4F	1:10	Bray & Kurtz (1945)
Bray-II	0.1N HCl + 0.03N NH_4F	1:17	NDSU (1980)
Olsen	0.5N $NaHCO_3$ pH 8.5	1:20	Olsen et al. (1954)
Citric acid	%1 citric acid	1:10	Dyer (1894)
Egner	0.02N Ca lactate + 0.02N HCl	1:20	Egner et al, (1960)
Morgan	0.54N HOAc + 0.7N NaOAc pH 4.8	1:10	Morgan (1941)
Modified Morgan	0.54N HOAc + 0.7N NH_4OAc + 0.03N NH_4F pH 4.8	1:10	McIntosh. (1969)
FeO strip	0.02 N $CaCl_2$ + FeO-coated filter paper strip	1:40	Chardon et al. (1996)

Table 2-2. Critical P concentration in some subtropical and tropical grasses.

Grass identification	Age or stage of growth	Critical P concentration, %	Reference
Bermudagrass	4-5 weeks	0.20-0.26	Martin and Matocha, 1973
Midland and common Bermudagrass	4-5 weeks	0.24-0.28	
Panicum Maximum, VAR	3-4 leaf	0.55	Smith, 1975
Trichoglume, cv. Petrie	4-5 leaf	0.32	
	6-7 leaf	0.15	
	I.P.F. † (57days)	0.20	Andrew and Robins, 1971
Kikuyugrass	I.P.F.(45 days)	0.22	
Pearl millet	4-5 weeks	0.16-0.20	Martin and Matocha, 1973
Staria spacelata, cv Nandi	4-leaf	0.46	Smith, 1975
	5-leaf	0.36	
	6-leaf	0.24	
	7-leaf	0.14	
Staria anceps, cv Nandi	I.P.F.(57 days)	0.21	Andrew and Robins, 1971
Dallisgrass	I.P.F.(57 days)	0.25	
Pangolagrass	I.P.F.(45 days)	0.16	
	4 weeks	0.12-0.16	Martin and Matocha, 1973
Buffelgrass	I.P.F.(57 days)	0.25	Andrew and Robins, 1971
	(whole plant tops inflorescences just appearing)	0.16	Smith, 1975
	youngest expanded leaves sampld	0.17	
Buffelgrass	I.P.F.(39 days)	0.26	Christie and Moorby, 1975
	46 days	0.30	
Rhodesgrass, cv Pioneer	I.P.F.(57 days)	0.22	Andrew and Robins, 1971
Molassesgrass	I.P.F.(57 days)	0.18	
Johnsongrass	boot stage	0.16-0.20	Martin and Matocha, 1973
Sorghum-sudangrass and sudangrass	4-5 weeks	0.14-0.20	

† I.P.F. means immediate preflowering stage of growth. Most analyses apply to whole plants unless otherwise specified.

CHAPTER 3
MATERIALS AND METHODS

This research consisted of one glasshouse hydroponic study and three glasshouse soil studies.

Glasshouse Hydroponic Study

A glasshouse hydroponic study was conducted at the Turfgrass Envirotron at the University of Florida, Gainesville, Florida. St. Augustinegrass var. Floratam was chosen as the testing cultivar based on its greatest use among all St. Augustinegrass cultivars. Six levels of P (0, 1.24, 6.2, 31, 155 and 775 mg m^{-3}) with five replicates were used to test for P response. Certified sod collected from the G.C. Horn Turfgrass Field Laboratory at the University of Florida in Gainesville was washed to remove soil from the root system. Sod was cut to a size of 15cm × 30cm rectangle and transferred to the hydroponics system on June 27, 2004.

Nalgene tubs (31cm × 16cm × 12cm) were used as the hydroponic containers. The outside surfaces of the containers were painted with black latex paint first and white afterwards to prevent light penetration. A 10-mm inner diameter polynvinyl chloride (PVC) pipe was used to make a rectangle frame (15cm × 30cm). The frame was attached with a piece of poly-hardware cloth and fitted on the corners of opening of the container to form a grass bedding surface. Since the frame was not fixed to the container, the frame/screen with grass could be removed to change solution or check solution pH periodically. The grass pieces (15cm × 30cm) were placed on the bedding surfaces. Nutrient solution level in the container was adjusted to touch the screen to induce root growth. Roots penetrated the screen and grew into the solution after about three weeks. Then the solution volume was reduced to approximately 1.5 cm below the frame to create an air zone between grass stolons and solution surface to avoid water damage and algae growth on the grass. An air compressor was used to supply air to the nutrient solution. A 5-m long with 7-mm inside diameter tygon tubing was fitted to the outlet of the air compressor at one end and

the other end was plugged. Along the 5-m plastic tube the containers were laid out on both sides with 15 tubs on each side. Another tube of the same diameter, but shorter length was used for each solution tub with one end fitting with a needle and the other end going to the solution. The needle penetrated the main tube and through the short tube air was blown into each solution. Smaller size of needles was used at the positions closer to the air compressor and larger sizes of needles for the far positions. By doing this, the air pressure due to distance difference between each tub and air compressor was roughly regulated and each solution achieved approximately the same air bubbling speed. Figure 3-1 shows the experiment layout.

Nutrient solution was slightly modified from what was reported by Breeze et al. (1984) by replacing Sequestrene Fe 138 with Sequestrene Fe 330, eliminating $CaSO_4$ and doubling the concentrations of nutrients they used. The nutrient solution was changed every other day to regulate pH, maintain nutrient concentrations and minimize salt accumulation. The P treatments were applied on October 17, 2004 at which time the turfgrass was exhibiting P deficiency. The study was terminated on March 14, 2005. The treatments were arranged in a randomized complete block design. Computer controlled overhead exhaust 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 22°C with a range of 18°C to 30°C. The relative humility was maintained at approximately 75%.

Top growth was clipped to 7.5 cm approximately monthly, once the dry matter production reached harvestable quantities, for a total of seven collections. Clippings were dried at 70°C for 48 h, and weighed. Root materials were clipped to 4 cm on September 8, 2004 and November 27, 2004. At root collection time the root density in the container was high. Root materials were washed with distilled water to remove the potentially adsorbed salts, dried at 70°C for 72 h and

weighed. The dry tissue and root 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 biweekly using a scale of 1 to 9 where 1 represents brown, dormant turf and 9 represents superior quality (Skogley and Sawyer, 1992).

Statistical analysis (analysis of variance) was performed by SAS (SAS Inst., 1987). Mean separation was done using Duncan's Multiple Range test at a 0.05 significant level. The relationship between turfgrass tissue growth rate and solution P and tissue P were determined using linear plateau analysis (PROC NLIN).

Glasshouse Soil Study 1

With the information of the critical minimum tissue P required by St. Augustinegrass from the hydroponic study, a study to determine the critical minimum soil test P concentration was initiated. This glasshouse soil study was conducted at the Turfgrass Envirotron at the University of Florida, Gainesville, Florida. The soil chosen in this study was collected from the A horizon of a soil mapped as "Pomona sand". It contained very low levels of Mehlich-1 P (2 mg P kg^{-1}). The Pomona series is in the family of Sandy, Siliceous, Hyperthermic Ultic Alaquods. Selected chemical properties for this soil (soil No. 1) are shown in Table 3-1. Nalgene tubs (53cm × 38cm × 12cm) were used as the growth container. Outside surfaces of the containers were painted with white latex paint first and black afterwards to prevent light penetration. Certified sod with high initial tissue P concentration was washed to remove soil, then cut to a size of 53cm × 38cm rectangle and transferred to the growth container on May 8, 2005.

After P deficiency was induced, P_2O_5 rate of 0, 0.31, 0.63, 1.25, and 2.5 g m^{-2} per four weeks were applied initially on April 12, 2006 and reapplied 3 times during the 16-week growth period. Treatments were arranged in a randomized complete block design with 5 replications for

each treatment. Computer controlled overhead exhaust 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 humility was maintained at approximately 75%. The experiment layout was shown in figure 3-2.

Top growth was clipped to 7.5 cm every other week for a total of 8 collections. 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).

Soil samples were taken at termination using a 3.0-cm via. soil probe. Soil samples were separated into soil depths of 0–2 cm and 2–10 cm. Mehlich-1 extractable P was determined for the soil samples in depth of 0–2 cm and 2–10 cm. Water extractable P and FeO-strip P were determined for the 0–2 cm soil depth.

At one week intervals, one-half pore volume of water was applied to all growth containers to aid in the collection of leachate. Leachate volume, pH, and EC were measured. A sub-sample was collected and frozen until soluble reactive P was analyzed.

Statistical analysis (analysis of variance) was performed by SAS (SAS Inst., 1987). Duncan's multiple range test with fixed variable was used for all the mean separation in this study. Means marked by the same letter are not significantly differently at P = 0.05.

Glasshouse Soil Study 2

An attempt was made to verify the critical soil test P concentration obtained in the glass house soil study 1. Two soils different from the one used in the previous study were chosen for

this study based on their low Mehlich-1 P concentrations (≤5 mg kg^{-1}). Samples from the A horizons were collected from soils mapped as Tavares sand and Pottsburg sand. Classifications of the soils were Tavares (Hyperthermic Uncoated Typic Quartzipsamments) and Pottsburg (Sandy, Siliceous, Thermic Grossarenic Alaquods), respectively. Selected chemical properties for soil No. 2 and 3 are shown in Table 3-1. This glasshouse soil study was conducted at the Turfgrass Envirotron at the University of Florida, Gainesville, Florida. Nalgene tubs (53cm × 38cm × 12cm) were used as the growth containers. Outside surfaces of the containers were painted with white latex paint first and black afterwards to prevent light penetration. Certified sod with high initial tissue P concentration was washed to remove soil, then cut to a size of 53cm × 38cm rectangle and transferred to the growth container on Septemer 28, 2005.

After P deficiency was induced, P_2O_5 rate of 0, 0.31, 0.63, 1.25, and 2.5 g m^{-2} per four weeks were applied initially on June 20, 2006 and reapplied 2 times during the 12-week growth period. The treatments were arranged in a 2 by 5 factorial design with 2 soils and 5 rates of P application. Each treatment was replicated 5 times. Computer controlled overhead exhaust 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 humility was maintained at approximately 75%.

Top growth was clipped to 7.5 cm every other week for a total of 8 collections. 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).

Soil samples were taken at termination using a 3.0-cm dia. soil probe. Soil samples were separated into soil depths of 0-2 cm and 2–10 cm. Mehlich-1 extractable P was determined for the soils samples in depth of 0–2 cm and 2–10 cm. Water extractable P and FeO-strip P were determined for the 0–2 cm soil depth.

At one week intervals, one-half pore volume of water was applied to all growth containers to aid in the collection of leachate. Leachate volume, pH, and EC were measured. A sub-sample was collected and frozen until soluble reactive P was analyzed.

Analysis of variance was performed by SAS (SAS Inst., 1987). Tukey's test was used for all the mean separation in this study. Means marked by the same letter are not significantly differently at P = 0.05.

Glasshouse Soil Study 3

Observing St. Augustinegrass growth responses on three soils low in P, a study was undertaken to evaluate growth on a soil containing a medium level of P. This soil study was conducted at the Turfgrass Envirotron at the University of Florida, Gainesville, Florida. The Tavares soil used in this experiment was chosen based on it having a medium level of Mehlich-1 P (17 mg P kg^{-1}) and was classified as Hyperthermic Uncoated Typic Quartzipsamments. Selected chemical properties for this soil (soil No. 4) are shown in Table 3-1. Nalgene tubs (53cm × 38cm × 12cm) were used as the growth containers. Outside surfaces of the containers were painted with white latex paint first and black afterwards to prevent light penetration. Certified sod with high initial tissue P concentration was washed to remove soil, then cut to a size of 53cm × 38cm rectangle and transferred to the growth container on May 8, 2005.

After P deficiency was induced, P_2O_5 rate of 0, 0.31, 0.63, 1.25, and 2.5 g m^{-2} per four weeks were applied initially on August 18, 2006 and reapplied 2 times during the 12 week growth period. Treatments were arranged in a randomized complete block design with 5

replications for each treatment. Computer controlled overhead exhaust 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 humility was maintained at approximately 75%.

Top growth was clipped to 7.5 cm every other week for a total of 6 collections. Clippings were dried at 70°C for 72 h, and weighed. Tissue growth rate was calculated by dividing tissue dry weight by growth days. 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).

Soil samples were taken at termination using a 3.0-cm diameter soil probe. Soil samples were separated into soil depths of 0–2 cm and 2–10 cm. Mehlich-1 extractable P was determined for both depths. Water extractable P and FeO-strip P were determined for the soil samples in the depth of top 0–2 cm.

At one week intervals, one-half pore volume of water was applied to all growth containers to aid in the collection of leachate. Leachate volume, pH, and EC were measured. A sub-sample was collected and frozen until soluble reactive P was analyzed.

Statistical analysis (analysis of variance) was performed by SAS (SAS Inst., 1987). Duncan's multiple range test was used for all the mean separation in this study. Means marked by the same letter are not significantly different at P = 0.05.

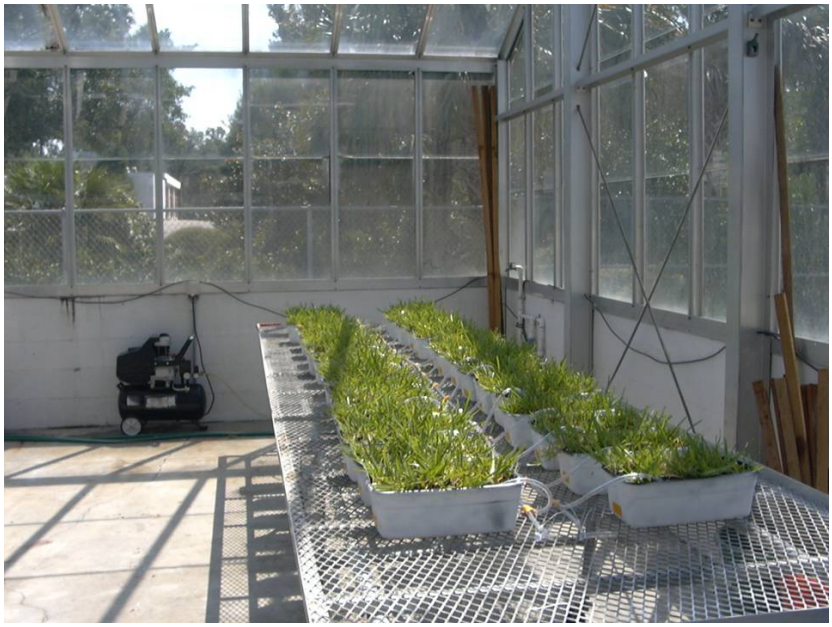

Figure 3-1. Glasshouse solution culture P study layout.

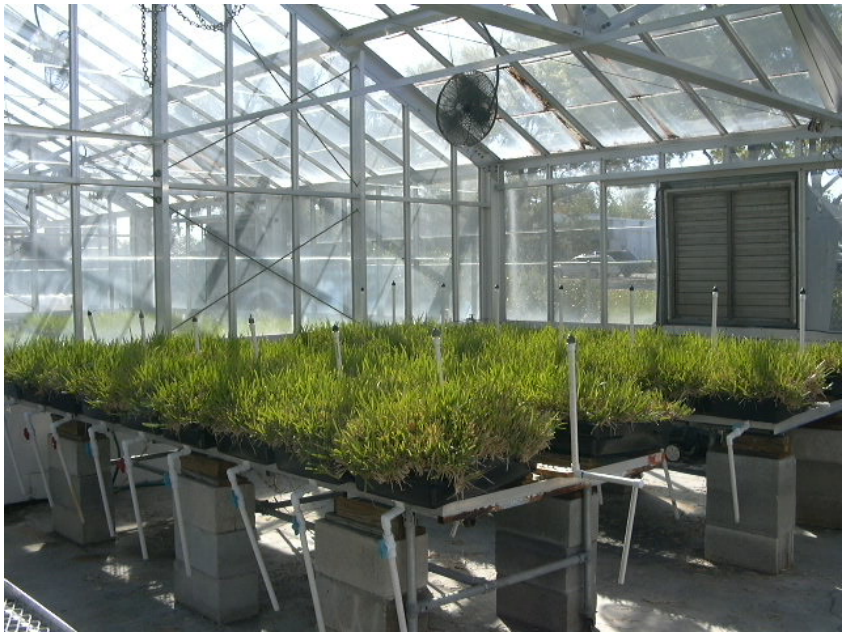

Figure 3-2. Glasshouse soil P study 1 layout.

Table 3-1. Selected chemical properties of soils used in the glasshouse soil study 1, 2, and 3.

Soil Study	Soil No.	Classification name	Series name	pH (1:2) †	OM (g kg^{-1}) ‡	Mehlich-1 P (mg kg^{-1})	Oxalate Al (mg kg^{-1})	Oxalate Fe (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 ignition.

CHAPTER 4
RESULTS AND DISCUSSION

Glasshouse Hydroponic Study

Turf Quality

St. Augustinegrass visual quality increased with each incremental increase in solution P concentration in the range from 0 to 775 mg m^{-3} (Figure 4-1). St. Augustinegrass treated with the two highest P concentrations, 155 and 775 mg m^{-3}, recovered from the P deficiency conditions and attained mean turf quality values of 6.8 and 7.2, respectively (Figure 4-1). The turf treated with zero P in solution suffered severely from P deficiency with a mean turf quality value of 2.5 (Figure 4-1). Turf treated with zero P declined in quality over time and by the end of the study was dead. Solution P levels of 1.24, 6.2, and 31 mg m^{-3} were generally insufficient in P for turf to recover from deficiency and promote optimum growth. Mean turf quality values from these treatments were below 5.5, which is widely used as a minimum value for acceptable turf quality.

Tissue P and Root P

The initial tissue P concentration of the St. Augustinegrass tested was as high as 4.8 g kg^{1} on a dry weight basis. After three harvests prior to treatment application, P deficiency (<1.0 g kg^{-1} on dry weight basis) was induced. Over time, tissue P concentration changed for the six P treatments as shown in Figure 4-2. Tissue P concentration of turfgrass receiving no P declined over time until it reached a value of 0.48 g kg^{-1} after the fourth harvest. By the end of the study most of the turfgrass was dead, but those portions which were still alive contained 0.45 g P kg^{-1}. This could be considered the minimum P concentration to keep St. Augustinegrass alive.

The relationship between tissue P levels and solution P concentration is presented in Figure 4-3. The highest tissue P level was achieved with application of 775 mg m^{-3} solution followed by

P treatment of 155 mg m^{-3}. There were no differences in P concentration among the four lowest P treatments. One possible reason for this observation is that the turfgrasses with the four lowest P levels remained P deficient during the experimental period.

The relationship between root P levels and solution P concentrations is shown in Figure 4-4. Root P levels increased with increasing solution P concentration. The highest P treatment resulted in the highest root P concentration (Figure 4-4). Root P concentration differences among the four lowest solution P levels were noted by Duncan's Multiple Range test compared with no significant differences among tissue P levels, which indicates that the primary use of P is for root growth rather than top growth when P is deficient. Moreover, the root P concentration (Figure 4-4) with the two highest P levels was lower than those in foliage tissue (Figure 4-3) when P supplies were sufficient. But the root P concentration resulting from the four lowest P levels was identical or even slightly higher than levels found in leaf tissue when P supplies were deficient. This suggests that roots require less P than tissue when P is sufficient, but when P is deficient root growth requires a higher level of P. It is possible that when P is deficient a higher quantity of P is required in order to produce more roots to overcome the P deficiency.

Tissue Growth Rate and Root Growth Rate

Phosphorus fertilization influence on tissue growth rate is rarely observed in St. Augustinegrass because of the generally medium to high available P status in Florida soils and relatively low P requirement by St. Augustinegrass. Tissue growth rate (Figure 4-5) was affected by solution P concentration. Tissue growth rate increased with solution P levels in a quadratic manner to a maximum value. According to linear plateau regression analysis (Figure 4-5), solution P concentrations beyond 111 mg m^{-3} did not result in increased tissue growth rate (r^2 = 0.88, $p<0.0001$, CV = 15.5). Asher and Loneragan (1967) reported that P at 155 mg m^{-3} produced maximum dry weights of clover (*Trifolium subterraneum*, L.), erodium (*Erodium*

botrys (Cav.) Bertol.) and yields of brome grass (*Bromus rigidus*, Roth) and cape weed (*Cryptostemma calendula* (L.) Druce) were close to maximum in a similar hydroponics study.

Root growth rates (Figure 4-6) were affected by solution P concentration although the effect was less as compared with tissue growth rates. Turfgrass receiving P at 31 mg m^{-3} attained the highest root growth rate among the P levels applied according to Duncan's Multiple Range test. Asher and Loneragan (1967) reported that P at 31 mg m^{-3} produced maximum top and root growth for sliver grass (*Vulpia (Festuca) myuros* (L.) Gmel.). Root P concentration in the presence of P at 31 mg m^{-3} was 0.7 g kg^{-1}, which indicates that roots require a smaller quantity of P for optimum growth than tissue (Figure 4-7). Only three mean categories were separated for root growth rates (Figure 4-6) indicating that the extent of the effect of solution P concentration on root growth was less than that on tissue growth. Additionally, turf receiving no P produced substantial root growth (Figure 4-6). The large reserve of P in the parent plant (approximately 5 g kg^{-1} P in tissue (Figure 4-1) and correspondingly high P level in stolons (not measured)) can be a P source for root growth in case there was no P application or P supplies were not sufficient.

Critical Tissue P level

A yield response curve in relation to concentration of P in the selected tissue is commonly used to determine the critical P concentration. Tissue growth rate was increased with tissue P concentration in a quadratic manner to a maximum value (Figure 4-7). 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 1.6 g kg^{-1} on dry weight basis for the optimum growth (R^2 = 0.88, p<0.0001, CV = 15.4).

Glasshouse Soil Study 1

Turf Quality

For each week across 16 weeks, the highest P application rate of 2.5 g m^{-2} 4-wk^{-1} resulted in the best turf quality (Table 4-1). There was no difference between turf quality ratings associated with the highest P rate and the second highest P rate except for the first week (Table 4-1). The third highest P application rate also achieved best turf quality except for the first three weeks (Table 4-1). With the P deficiency induced for St. Augustinegrass before P application, it took some time for St. Augustinegrass to recover from the P deficiency after P application. The higher the P rates applied, the shorter the time required for it to recover and produce the best quality. The second lowest P application rate of 0.31 g m^{-2} 4-wk^{-1} resulted in the best turf quality in 12 out of 16 weeks (Table 4-1), which provided some evidence that the minimum P application rate was somewhat above 0.31 g m^{-2} 4-wk^{-1} for this soil. The turf quality of the control treatment remained above 6.0 for the first 10 weeks and started to decline afterwards. By the last two weeks, the turf quality was below 5.5, which is widely used as a minimum value for acceptable turf quality (Table 4-1). Overall, the turf quality ratings were above 5.5 except for the turf with control during the last four weeks. This indicated that St. Augustinegrass could sustain for months with very low soil P concentrations and deficient P levels in plant tissue.

Top Growth Rate

St. Augustinegrass top growth responded to P application rates (Table 4-2). Turf receiving no P produced the lowest amount of top biomass across eight harvests (Table 4-2). The largest increase on top growth rate was observed with the first incremental P application (Table 4-2). Turf with three highest P application rates achieved the highest top growth rate across the eight

harvests. For six out of eight harvests, turf with the second lowest P application rate of 0.31 g m^{-2} 4-wk^{-1} produced the same top growth as higher P application rates (Table 4-2). The mean value of turf top growth rate with the P application rate of 0.31 g m^{-2} 4-wk^{-1} across eight harvests was 2.7 g m^{-2} day^{-1} and the highest mean value of top growth rate was 3.0 g m^{-2} day^{-1} (Table 4-2). The top growth rate for turf with the P application rate of 0.31 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. Moreover, when the overall means of top growth rate for each P application rate were compared, turf with the P application of 0.31 g m^{-2} 4-wk^{-1} produced tissue dry weight that was not significant different from those with higher P application rates by Duncan's multiple range test (Table 4-2). By either definition of critical minimum nutrient requirement or Duncan's multiple range test, P application rate of 0.31 g m^{-2} 4-wk^{-1} satisfied the minimum P requirement of St. Augustinegrass in this soil.

Tissue P Concentration

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 is shown in Table 4-3. With each incremental P application, tissue P concentration increased across the eight harvests. The highest tissue P level was achieved with application of 2.5 g P_2O_5 m^{-2} 4-wk^{-1} and was followed by application of 1.25, 0.63, and 0.31 g P_2O_5 m^{-2} 4-wk^{-1} (Table 4-3). 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 4-1), and reduced growth rate (Table 4-2). In

particular, the mean value of tissue P concentration with P application rate of 0.31 g P_2O_5 m^{-2} 4-wk^{-1} was 1.4 g kg^{-1}, which was slightly lower than the critical minimum tissue P concentration according to the previous glasshouse hydroponic study. This indicated that P application of 0.31 g P_2O_5 m^{-2} 4-wk^{-1} was about 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 rate of 0.31 g P_2O_5 m^{-2} 4-wk^{-1} satisfied the minimum P requirement of St. Augustinegrass in this soil.

The Critical Minimum Tissue P concentration

A yield response curve in relation to concentration of P in the selected tissue is commonly used to determine the critical P concentration. Tissue growth rate was increased with tissue P concentration in a quadratic manner to a maximum value (Figure 4-8). 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 ($R^2 = 0.77$, $p<0.0001$).

Soil Test P

Mehlich-I procedure is widely used in the southeast region of US for agronomic crop soil tests. Fe Oxide P and WEP procedures are used for environmental impact prediction. Soil Mehlich-I P, Fe Oxide P, and WEP concentrations as affected by P application are shown in figure 4-9. With increased P application rates, Mehlich-1 P, Fe Oxide P and WEP concentrations increased incrementally. For each P application, the Fe Oxide procedure extracted approximately

the same quantity of P as water, which means that the labile P portion with sorption/desorption process was soluble, suggesting there is little Al/Fe oxides in this soil. Mehlich-1 P concentrations were all higher than the concentrations of Fe oxide P or WEP, which was consistent with Pautler and Sims (2000).

Figure 4-11 shows the relationship among Mehlich-1 P, Fe Oxide P, and WEP concentrations. They were pairwise linear dependent with r^2 s of 0.91, 0.90, and 0.85 for WEP vs. Fe oxide P, Mehlich-1 P vs. Fe oxide P, and Mehlich-1 P vs. WEP, respectively. All the pairwise relationships were highly significant with p values less than 0.0001. Pautler and Sims (2000) reported a better relationship of Fe oxide P vs. WEP than that of Mehlich-1 P vs. WEP. This was true for this study. The explanation could be the nature of Fe oxide P procedure that it does not dissolve water insoluble P components. While, Mehlich-1 extractant contains diluted strong acids which could partially dissolve water insoluble P components.

In order to select the best soil test procedure for P recommendation on St. Augustinegrass, Mehlich-1 P, Fe Oxide P, WEP concentrations were related to turf tissue P concentration (Figure 4-11). All the pairwise relationships were highly significant with p values less than 0.0001, which means that all three soil P test methods could potentially be used as an index for P nutrition of St. Augustinegrass. Mehlich-1 P obtained the best correlation against tissue P concentration with r^2 of 0.84 better than 0.77 and 0.79 for Fe Oxide P and WEP respectively.

The Critical Minimum Soil Test P Concentrations

Application of the various P_2O_5 rates up to 2.5 g P_2O_5 m^{-2} 4-wk^{-1} resulted in a range of extractable soil P concentration (0.5 to 16.7 mg kg^{-1} for Mehlich-1, 0.4 to 7.7 mg kg^{-1} for Fe Oxide, and 0.4 to 7.6 mg kg^{-1} for WEP). Growth rate of St. Augustinegrass was affected by extractable soil P concentrations (Figure 4-12; Figure 4-13; Figure 4-14). Responses were described relatively well by the quadratic response and plateau model with the coefficients of

determination being generally high (0.71 for Mehlich-1, 0.68 for Fe Oxide, and 0.62 for WEP) and p values of less than 0.0001. Critical concentration of the extractable P was greatest for Mehlich-1 of 7 mg kg^{-1} compared 3 and 3 mg kg^{-1} for Fe Oxide P and WEP, respectively. This is to be expected, because Mehlich-1 extractant contains diluted strong acids which could dissolve water insoluble P compounds. Critical concentration of the extractable P for Fe Oxide and WEP was the same. This indicated that P adsorbed on soil particles was soluble. CSP applied was partially dissolved in soil solution and partially reacted with soil chemicals to form insoluble compounds.

Previously, Mehlich-1 soil P below 16 mg kg^{-1} was categorized as low and below 10 mg kg^{-1} as very low P. Phosphorus fertilization would be recommended in those cases. These data showed that P levels can be kept very low for St. Augustinegrass optimum growth. Phosphorus fertilization would not result in growth response above 7, 3, and 3 mg kg^{-1} for Mehlich-1, Fe Oxide, and WEP, respectively. Mehlich-1 P had the best correlation against both tissue P concentration and top growth rate in this soil, therefore it is the best soil P test for St. Augustinegrass among the three used in this study.

P Downward Movement

Soil samples in depth of 0-10 cm were initially taken and analyzed for Mehlich-1 P. However, Mehlich-1 P concentrations for the whole depth of 0-10 cm were generally very low, and there was no difference in Mehlich-1 P concentrations among P application rates by Duncan's multiple range test (data not shown). An attempt was made to investigate the downward movement by separating the soil depth into 0-2 cm and 2-10 cm. Soil Mehlich-1 P concentration as influenced by P application and soil sampling depth are shown in Figure 4-15. Control soils contained 0.6 mg kg^{-1} Mehlich-1 P, which indicated extremely low soil P availability without P application during the study. Soil Mehlich-1 P concentration in top 2 cm

depth increased with each incremental P application. Soil Mehlich-1 P concentrations in depth of 2–10 cm increased with P application, but were all very low in the range of 0.6 to 1.1 mg kg^{-1}. Considering 0.6 mg kg^{-1} was the baseline of Mehlich-1 P with control, the highest P application rate of 2.5 g P_2O_5 m^{-2} 4-wk^{-1} resulted in Mehlich-1 P of 1.1 mg kg^{-1} in soil depth of 2–10 cm. Moreover, for each P application other than control soil, Mehlich-1 P concentration in depth of 0–2 cm was higher than that in depth of 2–10 cm. This suggests that little to none of the CSP applied to the turfgrass moved downward and the majority remained in the top 2 cm of soil.

Leached P Mass and Concentration

Phosphorus treatments were applied every four weeks for a total of four times. Leachates were collected weekly. Sixteen leachates were collected during the study period. The sum of the soluble reactive P (SRP) leached during the first, second, third and fourth leaching collections is presented in Figure 4-16. Chung et al. (1999) has shown that a greater quantity of P leached from sand root-zone mixture during the first two leaching events. However, a natural soil was used in this study, for each P application a greater quantity of P leached during the first leaching event than those during following leachate collections. Soil receiving 2.5 g P_2O_5 m^{-2} 4-wk^{-1} leached a total of 11.8 mg P, followed by 5.9, 2, 1.3, and 0.9 mg P from application of 1.25, 0.63, 0.31 and 0 g P_2O_5 m^{-2} 4-wk^{-1}, respectively. The two highest P application rates resulted in larger quantities of P leached and no differences in P leached were detected among the three lower P application rates. In effect, soil with application rate of 0.63 g P_2O_5 m^{-2} 4-wk^{-1} did not leach a larger quantity of P than control soil. This result showed the importance of small P application rate to prevent P leaching to ground waters. Not to mention the P requirements for certain crops could be less than recommended, the best management practice could be to suggest multiple P applications with a smaller quantity each time. Leached SRP concentration as affected by P application rate and leaching event followed the same pattern as leached SRP mass (Figure 4-17). The highest P

concentration was detected in the leachates collected in the first leaching event. An application of 0.63 g P_2O_5 m^{-2} 4-wk^{-1} did not result in a higher SRP concentration than control soil. Leachates collected from soil receiving 2.5 and 1.25 g P_2O_5 m^{-2} 4-wk^{-1} contained as high as 0.89 and 0.5 mg P kg^{-1}, respectively, which could cause environmental concerns. Notice that both of these rates are commonly applied to St. Augustinegrass and application rate of 1.25 g P_2O_5 m^{-2} 4-wk^{-1} is the standard in summer months based on the 4:1:2 ratio of N: P_2O_5: K_2O.

Glasshouse Soil Study 2

Turf Quality

Quality ratings were influenced by P application rate for both soil No.2 and 3 (Table 4-4). Twelve weeks of turf quality data were collected. For individual weekly evaluations across the 12 week experiment period, P application of 0.63g P_2O_5 m^{-2} 4-wk^{-1} and above resulted in the best turf quality for both soils (Table 4-4). P application of 0.31 g m^{-2} 4-wk^{-1} achieved the best turf quality in 11 out of 12 weeks for both soils (Table 4-4), which provided some evidence that the minimum P application rate was somewhat above 0.31 g m^{-2} 4-wk^{-1} for these two soils. For the control turf, turf quality remained above acceptable level 5.5 for the first 4 and 3 weeks for soil No.2 and 3, respectively, and declined afterwards. Overall, the turf quality ratings were somewhat lower than that in the glasshouse soil study 1, which was mainly due to an incidence of disease. Turf with no P application barely recovered from the incidence of disease, which implied the importance of P nutrition in case of disease damage recovery.

Top Growth Rate

St. Augustinegrass top growth rate varied with P application and soil (Table 4-5). Control turf produced the lowest quantity of top dry mass across six harvests in both soil conditions (Table 4-5). 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} day^{-1} for soil No.2 and 3, respectively)

(Table 4-5). For soil No.2 the top growth rate for turf with P application rate of 0.31 g m^{-2} 4-wk^{-1} was reduced by approximately 10% from the optimum growth rate. Moreover, turf with P application rates of 0.31 g m^{-2} 4-wk^{-1} and above achieved equivalent mean top growth rates by Tukey's test. Therefore, by either definition of critical minimum nutrient requirement or Tukey's test, P application rate of 0.31 g m^{-2} 4-wk^{-1} satisfied the minimum P requirement of St. Augustinegrass in soil No.2. However, for soil No. 3 the top growth rate for turf with P application rate of 0.31 g m^{-2} 4-wk^{-1} was reduced by approximately 30% from the optimum growth rate of 2.9 g m^{-2} day^{-1}. When the 6-harvest means of top growth rates were subjected to Tukey's test, there were no differences among growth means receiving P application of 0.31 g m^2 4-wk^{-1} and above. This was probably due to a larger variation on top growth rate that occurred when grown in soil No. 3. This larger variation may have resulted from more severe disease damage in soil No. 3, which particularly influenced growth more on turf with lower P application rates (0.63 g m^{-2} 4-wk^{-1} and below) (Table 4-5). It has been previously shown that P application improved recovery of turf quality from disease. These data also showed the benefits of P application on top growth rate in case of disease incidence.

Tissue P Concentration

The initial tissue P concentration of the St. Augustinegrass was 4.1 g kg^{-1} on a dry weight basis. Over 9 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 4-6). In both soils, a maximum tissue P level was achieved (3.2 g kg^{-1}) in response to P_2O_5 applied at 2.5 g m^{-2} 4-wk^{-1}. Turfgrass receiving no P maintained a value of 1.0 g kg^{-1}, with which turfgrass showed P deficiency symptoms, reduced turf quality (Table 4-6), and reduced growth rate (Table 4-5). Tissue P concentration increased with each incremental P application across six

harvests for both soils. Maximum top growth rate was achieved at 0.31 g P_2O_5 m^{-2} 4-wk^{-1}, suggesting that application of additional P does not enhance top growth rate but P uptake. Greater tissue P concentrations and top growth rates were observed in soil No. 2 than No. 3, indicating a greater P uptake occurred in soil No. 2, possibly caused by a more severe incidence of disease in soil No.3.

The Critical Minimum Tissue P concentration

In a previous solution culture study, the critical tissue P concentration was determined to be 1.6 g kg^{-1}. In the glasshouse soil study 1, the critical minimum tissue P concentration was estimated to be 1.8 g kg^{-1}. In this study including two soils, the critical minimum tissue P concentration was 1.9 g kg^{-1} (Figure 4-18), according to non-linear plateau regression analysis ($R^2 = 0.70$, $p<0.0001$). The coefficient of determination could be improved from 0.70 to 0.75 by removing two outliers. The maximum top growth rate estimated in the quadratic relationship was 2.8 g kg^{-1}, which was the same as the optimum growth rates corresponding to the highest P application rate of 2.5 g P_2O_5 m^{-2} 4-wk^{-1}, suggesting a reasonable plateau.

Soil P Tests

Soil Mehlich-1 P, Fe Oxide P, and WEP varied with P application for soil No. 2 (Figure 4-19) and No. 3 (Figure 4-20). With increased P application soil test P levels increased for both soils. For each P rate, Fe Oxide procedure extracted approximately the same quantity of P as water, which was consistent with the findings in glasshouse soil study 1. This was possibly due to a low bonding energy of P sorption/desorption with absence of Al/Fe oxides in these soils. The portion adsorbed on soil particles eventually dissolved in the water extraction procedure. Mehlich-1 P concentration was more or less double the concentration of Fe oxide P or WEP, which was consistent with the observations in the glasshouse soil study 1. The explanation could be the nature of Fe oxide P procedure that is based upon sorption/desorption process and does

not dissolve any water insoluble P components. However, Mehlich-1 extractant contains diluted strong acids which could partially dissolve water insoluble P components.

Figure 4-21 showed the relationships among Mehlich-1 P, Fe Oxide P, and WEP concentrations for soil No.2. They were pairwise linear dependent. All the pairwise relationships were highly significant with p values less than 0.0001. In the previous glasshouse soil study 1, a better correlation of Fe oxide P vs. WEP than that of Mehlich-1 P vs. WEP was observed. This was true for soil No. 2 in this study with r^2 s of 0.65 and 0.54 for WEP vs. Fe oxide P and Mehlich-1 P vs. WEP, respectively. For soil No.3, an identical coefficient of determination (r^2) of 0.68 was obtained for relationships of Fe Oxide P vs. WEP and Mehlich-1 P vs. WEP. A higher coefficient of determination was recorded for Mehlich-1 P vs. Fe Oxide P (r^2=0.72) (Figure 4-22).

In the glasshouse soil study 1, Mehlich-1 P correlated better with tissue P concentration than Fe Oxide P and WEP (Figure 4-12). Tissue P concentration and soil test P concentrations for soil No. 2 (Figure 4-23) and soil No. 3 (Figure 4-24) showed the same trend. For soil No. 2, Mehlich-1 P obtained the best correlation against tissue P concentration with r^2 of 0.85, which was higher than 0.46 and 0.35 for Fe Oxide P and WEP, respectively. For soil No. 3, r^2 of 0.71 was obtained for Mehlich-1 P vs. tissue P, which was higher than 0.67 and 0.63 for Fe Oxide P and WEP vs. tissue P, respectively. Overall, the three soil P tests concentration were correlated to tissue P concentration with Mehlich-1 P obtaining the best prediction on tissue P levels.

The Critical Minimum Soil Test P Concentrations

The growth rate of St. Augustinegrass was affected by soil Mehlich-1 P concentration (Figure 4-25 for soil No. 2; Figure 4-26 for soil No. 3), Fe Oxide P (Figure 4-27 for soil No. 2), and WEP concentration (Figure 4-28 for soil No. 2). Application of phosphate up to 2.5 g P_2O_5 m^{-2} 4-wk^{-1} resulted in a range of extractable soil P concentrations (0.2 to 10.5 and 0.6 to 9.5 mg

kg^{-1} for Mehlich-1 in soil No. 2 and 3, respectively; 0.6 to 5.2 and 0.8 to 5.5 mg kg^{-1} for Fe Oxide in soil No. 2 and 3, respectively; 0.8 to 4.0 and 0.9 to 4.6 mg kg-1 for WEP in soil No. 2 and 3, respectively). Growth rate vs. Mehlich-1 P in both soils and growth rate vs. Fe Oxide P and WEP in soil No.2 were described relatively well by the quadratic response and plateau model with the coefficients of determination being generally acceptable (0.54 and 0.60 for Mehlich-1 in soil No. 2 and 3 respectively, 0.72 for Fe Oxide in soil No. 2, and 0.41 for WEP in soil No. 2). When top growth rate was related to Fe Oxide P and WEP in soil No. 3, top growth rate increased with increasing Fe Oxide P or WEP concentrations and thus failed to converge to a plateau (data not shown). This was possibly due to a low correlation between growth rate and Fe Oxide P or WEP concentration and a large variation among replications. The critical Mehlich-1 P concentration obtained for soil No. 2 and 3 were 8 and 9 mg kg^{-1}, respectively, which was close to the critical Mehlich-1 P concentration (7 mg kg^{-1}) determined in the previous glasshouse soil study 1. For soil No. 2 the critical Fe Oxide P and WEP concentration was 3 mg kg^{-1}. These data suggest that optimum growth of St. Augustinegrass can be attained at very low soil lest P levels. Phosphorus fertilization would not result in growth response above 8, 3, and 3 mg kg^{-1} for Mehlich-1, Fe Oxide, and WEP, respectively for soil No. 2. Mehlich-1 P had the best correlation against both tissue P concentration and top growth rate in both soils with exception of correlation of top growth rate against Fe Oxide P was better than that against Mehlich-1 P. Overall, Mehlich-1 P test was the best soil P test for St. Augustinegrass among the three extractants used.

P Downward Movement

In the glasshouse soil study 1, CSP applied to the turfgrass did not move downward and the majority stayed in the top 2 cm in that soil. In this study soil samples were separated into 0–2 cm and 2–10 cm depths. Soil Mehlich-1 P concentration as influenced by P application rate and soil sampling depth are shown in Figure 4-29 (soil No. 2) and Fig. 4-30 (soil No. 3). Mehlich-1 P

concentration (0-2 cm depth) with P application rate of 2.5 g P_2O_5 m^{-2} 4-wk^{-1} was increased from 1 to 7.9 and 1.1 to 9.3 mg kg^{-1} for soil No. 2 and 3, respectively. Many studies have shown that the amount of fertilizer P required for each unit increase of soil test P level varies with soil texture, soil test method employed, as well as the rate of fertilizer P applied. In a 29-yr study on Ultisols in Alabama, Cope (1981) found that 24 and 20 kg P ha^{-1} raised Mehlich-1 soil test P by 1 mg P kg^{-1} when P was applied at 31 and 54 kg P ha^{-1} yr^{-1}, respectively. An application of 4 kg P ha^{-1} was required to raise the Bray I extractable P of medium-textured Mollisols and Alfisols 1 kg ha^{-1} (Peck et al., 1971). Cox (1994) showed that increases in Mehlich-III with each unit of applied P were 0.7 units for soils with 10% clay, and it decreased exponentially to 0.2 units for soils with >50% clay. In this study total applications of 9.4, 18.8, 37.5, and 75 kg P_2O_5 ha^{-1} raised the levels of soil Mehlich-1 P in top 2 cm soils by 2, 2, 4, and 7 mg P kg^{-1} soil, respectively, for soil No. 2 and by 2, 3, 5, and 8 mg P kg^{-1} soil, respectively, for soil No. 3 after 12 week of P fertilization. Soil Mehlich-1 P concentrations in depth of 2-10 cm increased with P application of 2.5 g P_2O_5 m^{-2} 4-wk^{-1} for soil No. 2, but soils with lower P rates did not result in increased Mehlich-1 P concentration (Fig. 4-29). For soil No. 3 P application did not influence the Mehlich-1 P levels in soil depth of 2-10 cm (Figure 4-30). This suggests that most of CSP applied to the turfgrass stayed in the top 2 cm soil depth and that a low application P rate would be helpful in preventing P downward movement.

Leached P Mass and Concentration

Phosphorus treatments were applied every four weeks for a total of three times. Leachates were collected weekly after each P application. Twelve leachates were collected during the study period. The sum of the soluble reactive P (SRP) leached during the first, second, third and fourth leaching collections is presented in Figure 4-31 (soil No. 2) and Figure 4-33 (soil No. 3), respectively. In the glasshouse soil study 1, it was observed that for each P application rate a

substantial greater quantity of P leached during the first leaching event and that little P leached in subsequent leachate collections. This was true for both soils in this study. Soil No. 2 which receiving 2.5 g P_2O_5 m^{-2} 4-wk^{-1} leached an average of 8.4 mg P, followed by 4.3, 1.6, 1.5, mg P from application of 1.25, 0.63, 0.31 g P_2O_5 m^{-2} 4-wk^{-1}, respectively, among which 48%, 44%, 44%, and 34% was leached in the first leaching event. Soil No. 3 leached an average of 10.3 4.3, 3.2, 1.8, mg P from applications of 2.5, 1.25, 0.63 and 0.31 g P_2O_5 m^{-2} 4-wk^{-1}, respectively, among which 42%, 47%, 47%, and 55% was leached in the first leachate collection. Not only was there a higher percentage of P mass leached in the first leaching event, but also the SRP concentration was higher in the first leachate than the subsequent leachates in soil No. 2 (Figure 4-32) and soil No. 3 (Figure 4-34). These findings suggest the importance of P application timing. To avoid P application before a rain event would be beneficial in preventing P leaching and runoff.

P application of 1.25 and 2.5 g P_2O_5 m^{-2} 4-wk^{-1} resulted in larger quantities of P leached and higher SRP concentration in soil No. 2 and there were no differences among leached P mass and SRP concentrations resulted from the three lower P application rates. For soil No. 3, P application of 2.5 g P_2O_5 m^{-2} 4-wk^{-1} resulted in a larger quantity of P loss and higher SRP concentration through leaching and there were no differences among leached P mass and SRP concentrations at the lower P application rates. This suggests that P loss through leaching can be prevented by small P application rate.

Glasshouse Soil Study 3

Turf Quality

Quantity of applied P influenced St. Augustinegrass quality (Table 4-7). A P_2O_5 application of 0.31 g m^{-2} 4-wk^{-1} resulted in the best turf quality in 10 out of 12 weeks (Table 4-7). Duncan's multiple range test of turf quality rating versus rate of P applied revealed differences in

mean turf quality rating up to 0.31 g P_2O_5 m^{-2} 4-wk^{-1}. Application of additional P beyond 0.31 g P_2O_5 m^{-2} 4-wk^{-1} did not increase turf quality. A total of 0.93 g P_2O_5 m^{-2} was applied, and this equates to an N: P_2O_5 application ratio of 16:1, which is substantially higher than common used 4:1 ratio. The previous glasshouse study 1 and 2 reported the same response to P application for St. Augustinegrass growing in course 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, it was believed that this soil still contained a substantial amount of plant available P, which was confirmed by soil analysis at the end of the study. The soil Mehlich-1 P concentration in control soils was 2.7 mg kg^{-1}, obviously due to a relatively high residue soil P concentration in the beginning of the study.

Top Growth Rate

St. Augustinegrass top growth rate responded to P application (Table 4-8). Duncan's multiple range test of top growth rate versus P application rate revealed differences in mean top growth rate up to 0.31 g P_2O_5 m^{-2} 4-wk^{-1}. Application of additional P beyond 0.31 g P_2O_5 m^{-2} 4-wk^{-1} did not increase top growth (Table 4-8). Relatively smaller growth rate reduction (approximately 25%) was observed in controls in this study compared with those in previous studies. This was due to a higher initial soil Mehlich-1 P concentration in this soil so that P deficiency on St. Augustinegrass was mildly developed. A CV of less than 10% suggests that there is a small variation among replications.

Tissue P Concentration

The initial tissue P concentration of the 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 4-9). Tissue P concentration increased with each incremental P application across six harvests. A maximum tissue P level (3.4 g kg^{-1}) was achieved in response to phosphate applied at 2.5 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 study 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.

Critical Minimum Tissue P Concentration

In the previous solution culture study, the critical tissue P concentration was determined to be 1.6 g kg^{-1}. In the glasshouse soil study 1 and 2, the critical minimum tissue P concentration was estimated to be 1.8 and 1.9 g kg^{-1}, respectively. The critical minimum tissue P concentration in study 3 was 1.8 g kg^{-1} (Figure 4-35), according to non-linear plateau regression analysis (r^2 = 0.48, $p<0.001$). The coefficient of determination was lower than that found in previous soil study 1 and 2. This was possibly due to three or four outliers. 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 study 1 and 2, respectively), suggesting a reasonable plateau.

Soil P Tests

Soil Mehlich-1 P, Fe Oxide P, and WEP varied with P application in soil study 3 (Figure 4-36). With each incremental increased P application soil Mehlich-1 P levels increased. Higher soil test P values were only observed for the application of 2.5 g P_2O_5 m^{-2} 4-wk^{-1} in Fe Oxide P, 1.25 and 2.5 m^{-2} 4-wk^{-1} in WEP, respectively (Figure 4-36). In the glasshouse soil study 1 and 2, Fe Oxide strip procedure and water extraction procedure extracted approximately the same quantity of P in those soil conditions. However, in this study Fe Oxide procedure extracted

greater quantities of P than water for each P application, which suggests a higher bonding energy of P sorption/desorption with the Al/Fe oxides in this soil. Some portion of P ions adsorbed on soil particles was not extracted by water extraction procedure but by Fe Oxide strip procedure. Mehlich-1 P concentration was more or less double the concentration of WEP, which was consistent with the observations in the glasshouse soil study 1 and 2.

Figure 4-37 shows the relationship among Mehlich-1 P, Fe Oxide P, and WEP concentrations in glasshouse soil study 3. They were pairwise linear dependent. In the previous glasshouse soil study 1 and 2, a better correlation of Fe oxide P vs. WEP than that of Mehlich-1 P vs. WEP was observed. This was true in this study with r^2 s of 0.52 and 0.35 for WEP vs. Fe oxide P and Melich-1 P vs. WEP, respectively. Moreover, the relationship of Fe oxide P vs. WEP ($p<0.0001$) had a smaller p value than that of Mehlich-1 P vs. WEP ($p<0.01$). A smaller coefficient of determination for each pairwise linear regression was obtained than those in the glasshouse soil study 1 and 2. This was possibly due to narrower ranges of soil test P extracted in this soil with Mehlich-1 P, Fe Oxide P and WEP mostly varied in 3, 1.5, and 1.5 mg P kg^{-1}, respectively (Figure 4-37). These narrow ranges of soil test P revealed a strong bonding force of P sorption/desorption and a small solubility of P compounds in water and dilute acids. These narrow ranges of Fe Oxide P and WEP also affect the correlations against tissue P concentration. The coefficients of determination for Fe Oxide P vs. Tissue P and WEP vs. Tissue P were 0.21 and 0.23, respectively, which were lower than those previously observed in the glasshouse study 1 and 2 (Figure 4-38). Soil Mehlich-1 P obtained the best correlation against tissue P concentration with r^2 of 0.70, higher than 0.21 and 0.23 for Fe Oxide P and WEP, respectively (Figure 4-38). Overall, the three soil test P concentration were correlated with tissue P

concentration ($p<0.05$) with Mehlich-1 P obtaining the best prediction on tissue P levels, which was consistent with observations in the previous studies.

The Critical Minimum Mehlich-1 P Concentration

Not only were the correlations of tissue P concentration against soil test P reduced by the narrow range of soil test P concentrations, but also the relationship between top growth rate and soil test P concentrations were reduced. Soil Fe Oxide P and WEP were poorly correlated with top growth rate. Top growth rate continued to increase with increased Fe Oxide P or WEP concentrations so that it did not converge to a plateau (data not shown). Therefore, it was not possible to establish a critical minimum level for Fe Oxide P and WEP. Growth rate vs. Mehlich-1 P was described well 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 soil No. 1, 2, and 3, respectively. This was expected because this soil contained a larger quantity of Al/Fe oxides and has a larger P buffering capacity. For each unit of soil test P level decrease, it supplied a larger quantity of P for plant uptake. These data suggest that P levels can be kept very low for St. Augustinegrass optimum growth. Phosphorus fertilization would not result in growth response above 5 mg kg^{-1} for Mehlich-1 P in this soil. Mehlich-1 P had the best correlation against both tissue P concentration and top growth rate and therefore is the best soil test method for St. Augustinegrass among the three tests used.

P Downward Movement

Soil samples were separated into 0–2 cm and 2–10 cm depths. Soil Mehlich-1 P concentration as influenced by P application and soil sampling depth was shown in Figure 4-40. Compared with control, Mehlich-1 P concentration (0–2 cm depth) with P application of 2.5 g P_2O_5 m^{-2} 4-wk^{-1} increased from 2.5 to 5.6 mg kg^{-1}. Total applications of 9.4, 18.8, 37.5, and 75

kg P_2O_5 ha^{-1} raised the levels of soil Mehlich-1 P in top 2 cm soils by 0.6, 1, 1.6, and 3.1 mg P kg^{-1} soil, respectively, after 12 weeks of P fertilization. Soil Mehlich-1 P concentration in top 2 cm soils increased with P application, however, P levels in the 2-10 cm depth was not affected (Figure 4-40). This suggests that CSP applied to the turfgrass stayed in the top 2 cm soil depth and downward movement of P was minimal.

Leached P Mass and Concentration

Phosphorus treatments were applied every four weeks for a total of three times. Leachates were collected one, two, three and four weeks after each P application. Twelve leachates were collected. The sum of the SRP quantity leached during the first, second, third and fourth leaching collections is presented in figure 4-41. It was observed that for each non-zero P application substantially greater quantities of P leached during the first two leaching events than in the following two leachate collections. This was consistent with the glasshouse soil study 1 and 2. Soils applied with 2.5 g P_2O_5 m^{-2} 4-wk^{-1} leached an average of 9.5 mg P, followed by 4.1, 3.5, 1.9 mg P from application of 1.25, 0.63, 0.31 g P_2O_5 m^{-2} 4-wk^{-1}, respectively, among which 71%, 68%, 74%, and 63% was leached out in the first two leaching events. Not only was there a substantial higher percent of P mass leached in the first two leaching events, but also the SRP concentration was higher in the first two leachates than followings (Figure 4-42). These findings suggest timing could be an issue for P application. To avoid P application before a rain event would be beneficial in preventing P leaching.

For each P application rate, the overall percentage of P loss due to leaching for application of 0.31, 0.63, 1.25, and 2.5 g P_2O_5 m^{-2} 4-wk^{-1} were 1.9%, 1.8%, 1.0% and 1.2%, respectively. The percentage were relatively small, but P application of 1.25 and 2.5 g P_2O_5 m^{-2} 4-wk^{-1} resulted in larger quantities of P leached and P application of 2.5 g P_2O_5 m^{-2} 4-wk^{-1} led to higher SRP concentration. P application of 0.63 g P_2O_5 m^{-2} 4-wk^{-1} and below did result in neither a

greater P quantity loss nor a higher SRP concentration than control. This suggests that small P application rate was effective in preventing P loss through leaching.

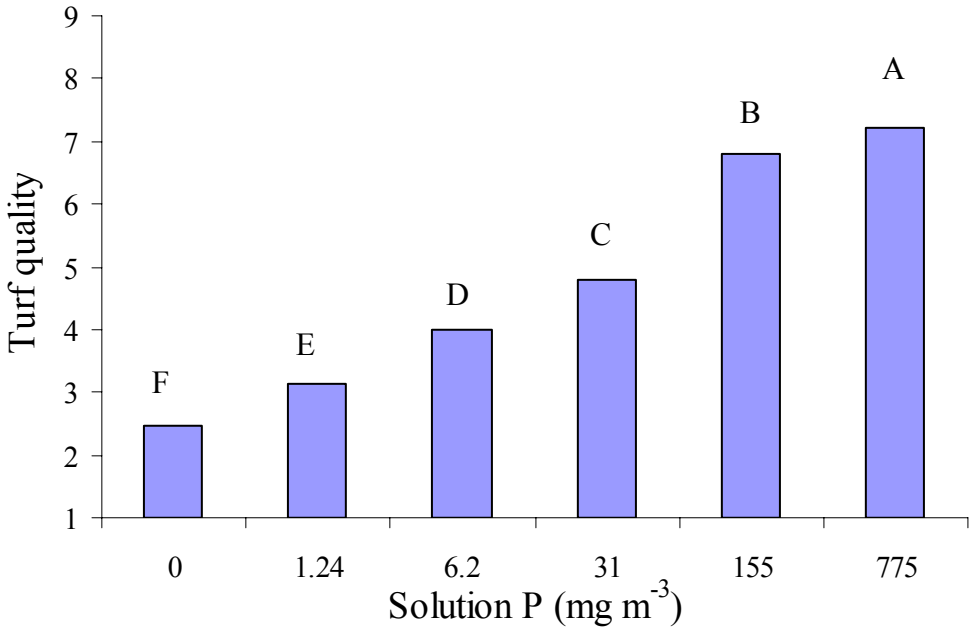

Figure 4-1. Turf quality response to solution P concentration. Turf quality is the mean of five replications over time after treatments were applied. Means marked by the same letter are not significantly differently at P = 0.05 according to Duncan's Multiple Range Test.

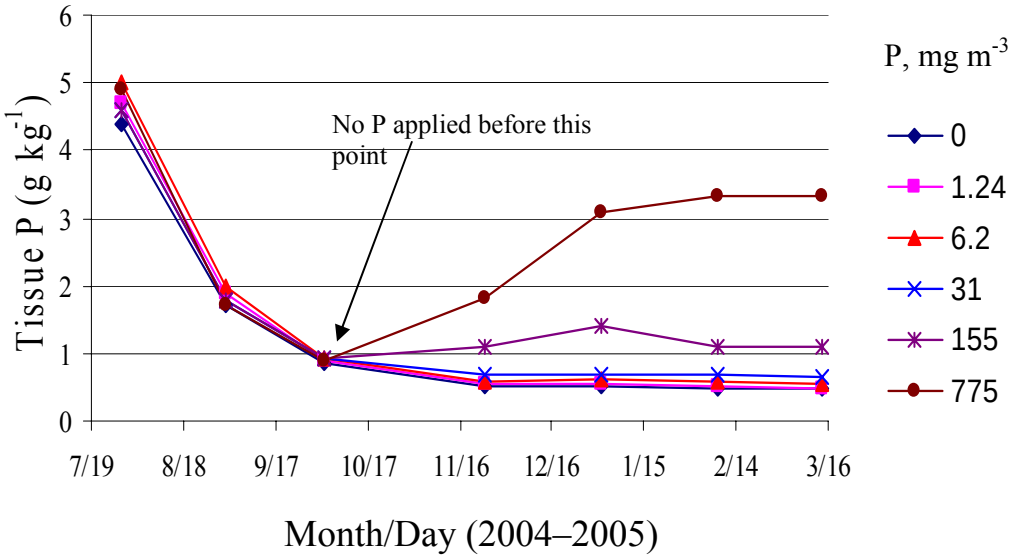

Figure 4-2. Tissue P response to solution P concentration and time.

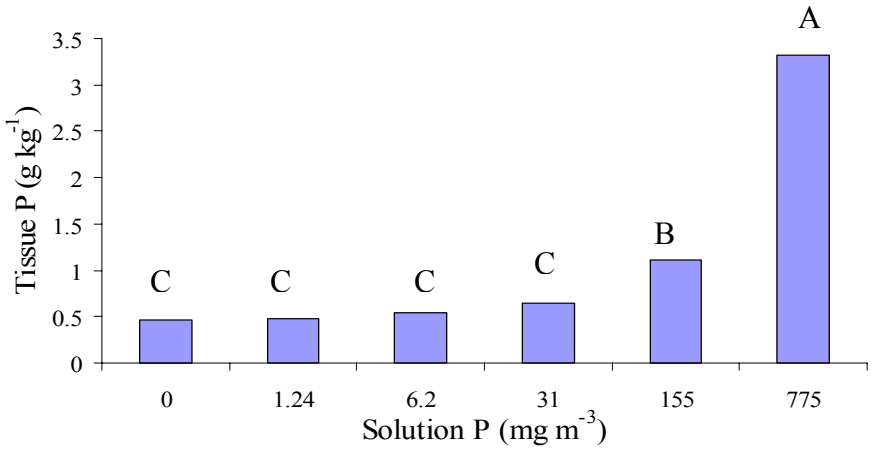

Figure 4-3. Relationship of solution P and tissue P concentration on day 148. Means marked by the same letter are not significantly differently at P = 0.05 according to Duncan's Multiple Range Test.

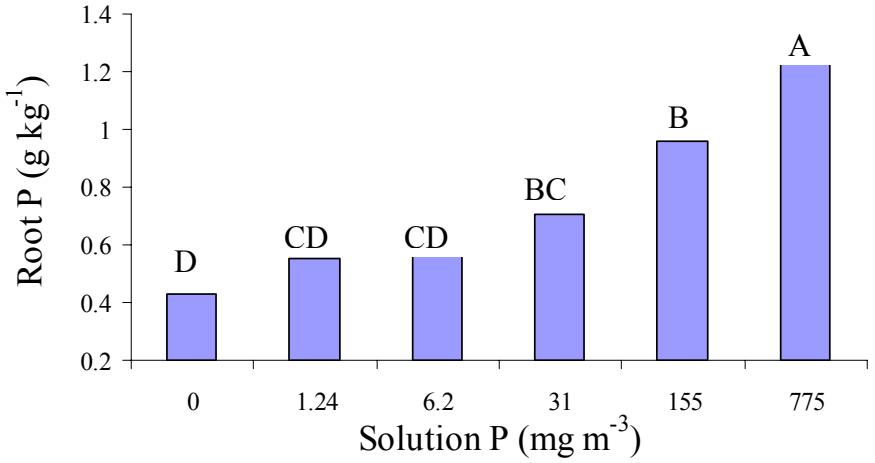

Figure 4-4. Relationship of solution P and root P concentration on day 148. Means marked by the same letter are not significantly differently at P = 0.05 according to Duncan's Multiple Range Test.

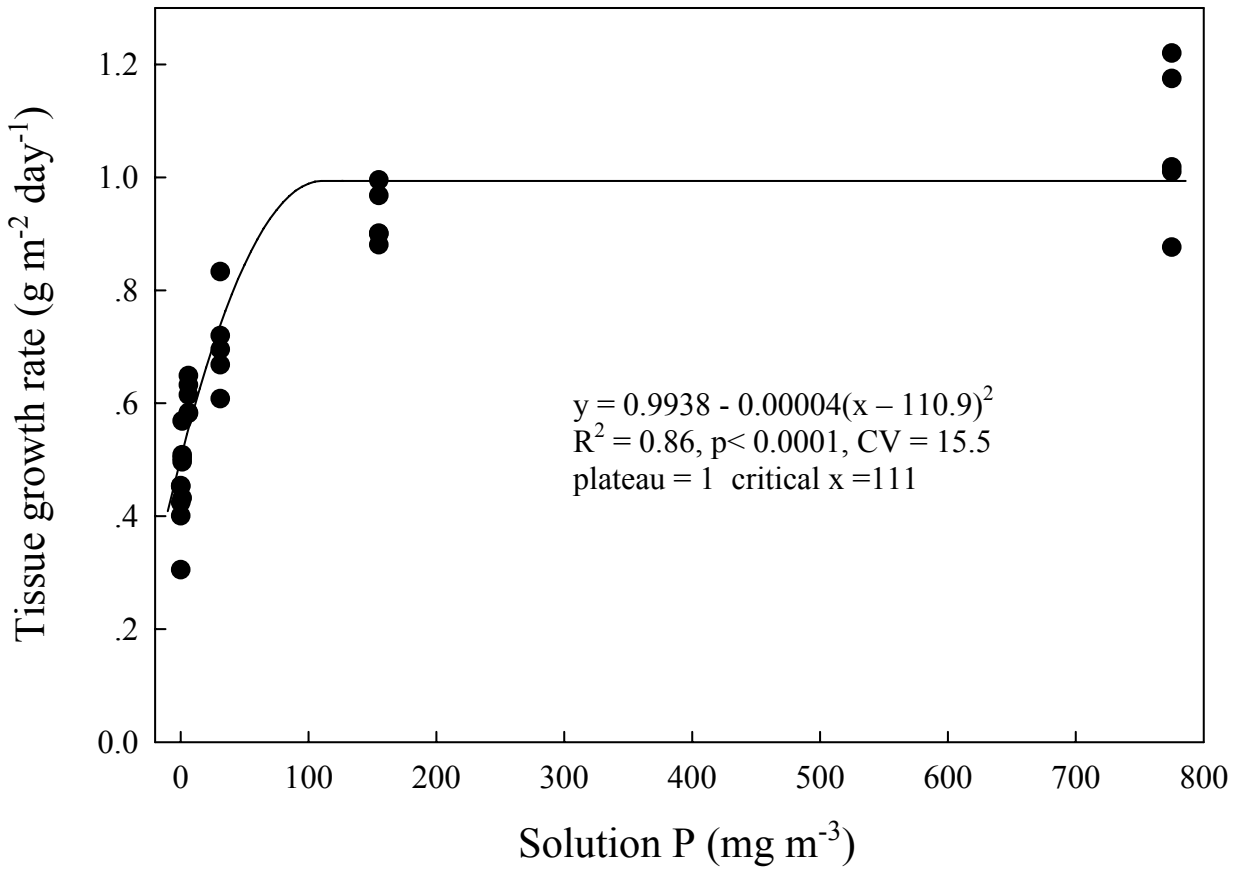

Figure 4-5. St. Augustinegrass tissue growth rate relative to solution P concentration.

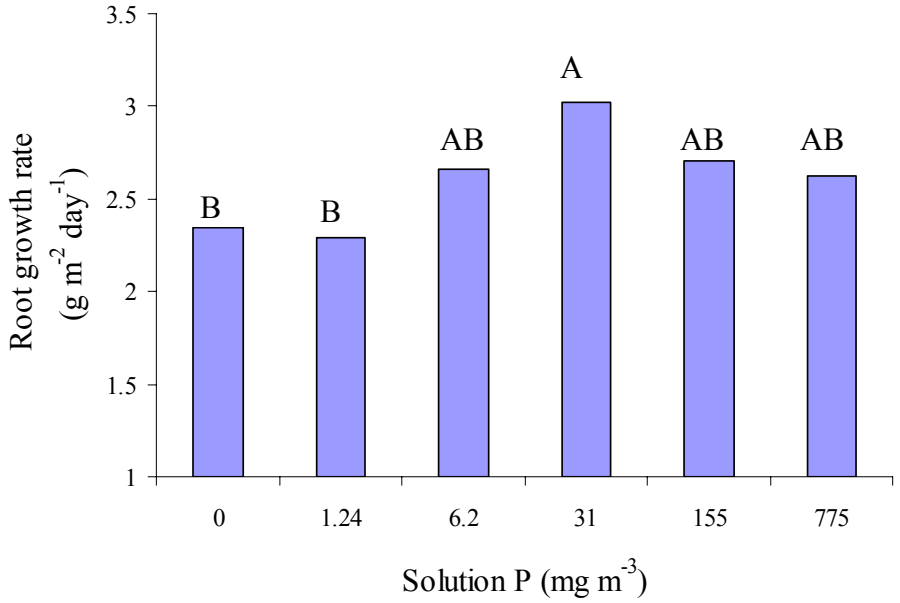

Figure 4-6. Root growth rate relative to solution P concentration. Means marked by the same letter are not significantly differently at P = 0.05 according to Duncan's Multiple Range Test.

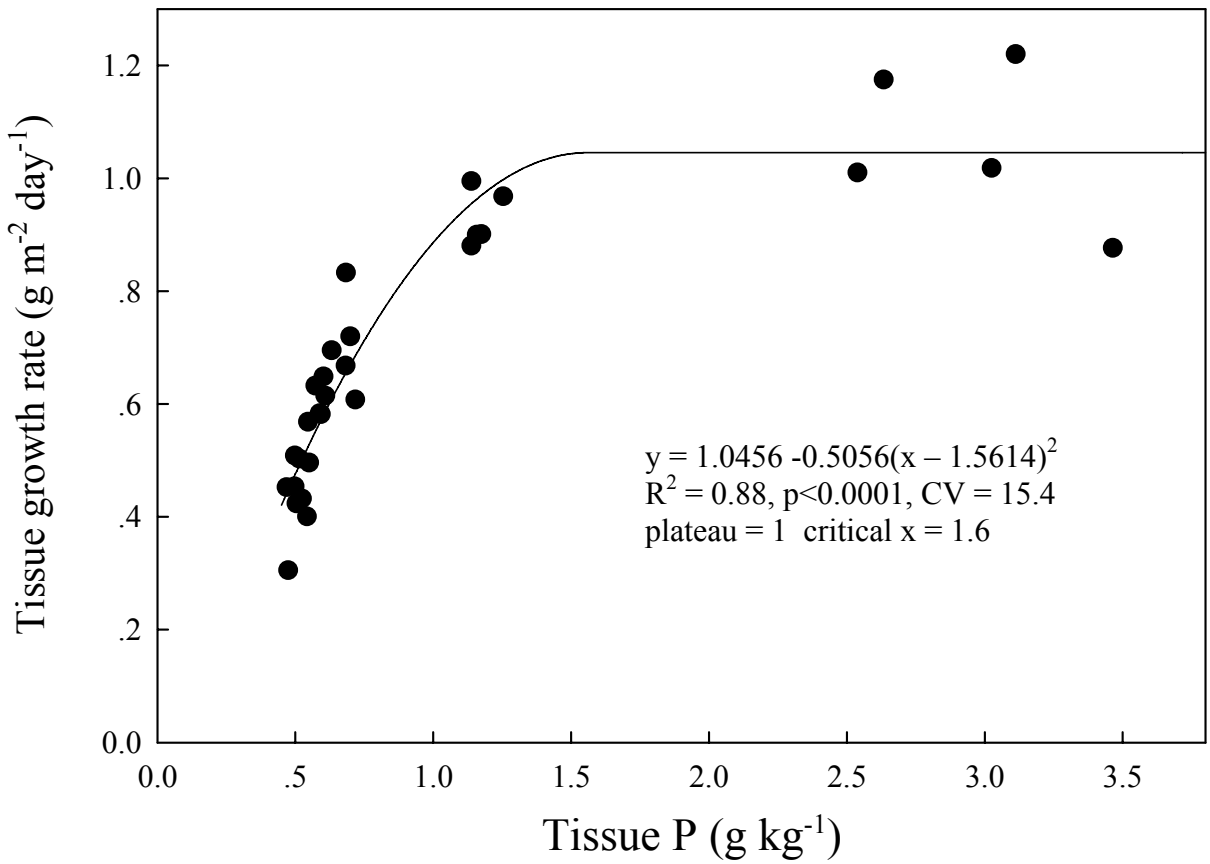

Figure 4-7. St. Augustinegrass tissue growth rate relative to tissue P concentration.

Table 4-1. Visual quality rating of St. Augustinegrass as influenced by P application rate in 2005–2006 glasshouse soil study 1.

P_2O_5 rates	Week †																
(g m^{-2} 4-wk^{-1})	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Mean
0	6.4c	6.5c	5.9c	7b	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
0.31	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
0.63	6.9b	7.3b	7.2b	7.6ab	7.2a	7.7a	7.2ab	7.6ab	7.2a	7.6a	7.5ab	7.7a	7a	7.9a	7.5a	7.4a	7.4b
1.25	6.9b	7.7ab	7.7ab	7.8a	7.6a	7.8a	7.6a	7.9ab	7.6a	8a	7.8ab	7.8a	7.5a	8.1a	7.5a	7.7a	7.7ab
2.5	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	6.0	8.8	4.7

†Within columns, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

Table 4-2. Top growth rate of St. Augustinegrass as influenced by P application rate in 2005–2006 glasshouse soil study 1.

P_2O_5 rates	Harvest †($g\ m^{-2}\ day^{-1}$)								
($g\ m^{-2}\ 4\text{-}wk^{-1}$)	1	2	3	4	5	6	7	8	Mean
0	2.2b	2.1b	2.1b	1.9b	2.0c	2.1c	2.1b	1.9b	2.1b
0.31	2.9ab	2.6ab	2.6a	2.3ab	2.4bc	2.5bc	2.9a	2.7a	2.7a
0.63	3.0a	2.6ab	2.9a	2.4ab	2.7ab	2.7ab	3.0a	3.0a	2.7a
1.25	3.0a	2.9a	3.0a	2.5ab	2.9a	3.0ab	3.1a	3.1a	3.0a
2.5	3.4a	3.0a	3.0a	2.5a	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

†Within columns, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

Table 4-3. Tissue P concentration of St. Augustinegrass as influenced by P application rate in 2005–2006 glasshouse soil study 1.

P_2O_5 rates	Harvest †($g\ kg^{-1}$)								
($g\ m^{-2}\ 4\text{-}wk^{-1}$)	1	2	3	4	5	6	7	8	Mean
0	1.1d	1.1d	1.1d	1.0d	1.0d	1.0d	0.8d	1.0e	1.0e
0.31	1.5cd	1.5cd	1.5c	1.4c	1.5c	1.3cd	1.3d	1.5d	1.4d
0.63	1.7c	1.6c	1.7c	1.7c	1.7c	1.8c	1.8c	2.1c	1.8c
1.25	2.5b	2.3b	2.6b	2.3b	2.4b	2.4b	2.7b	3.0b	2.5b
2.5	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

†Within columns, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

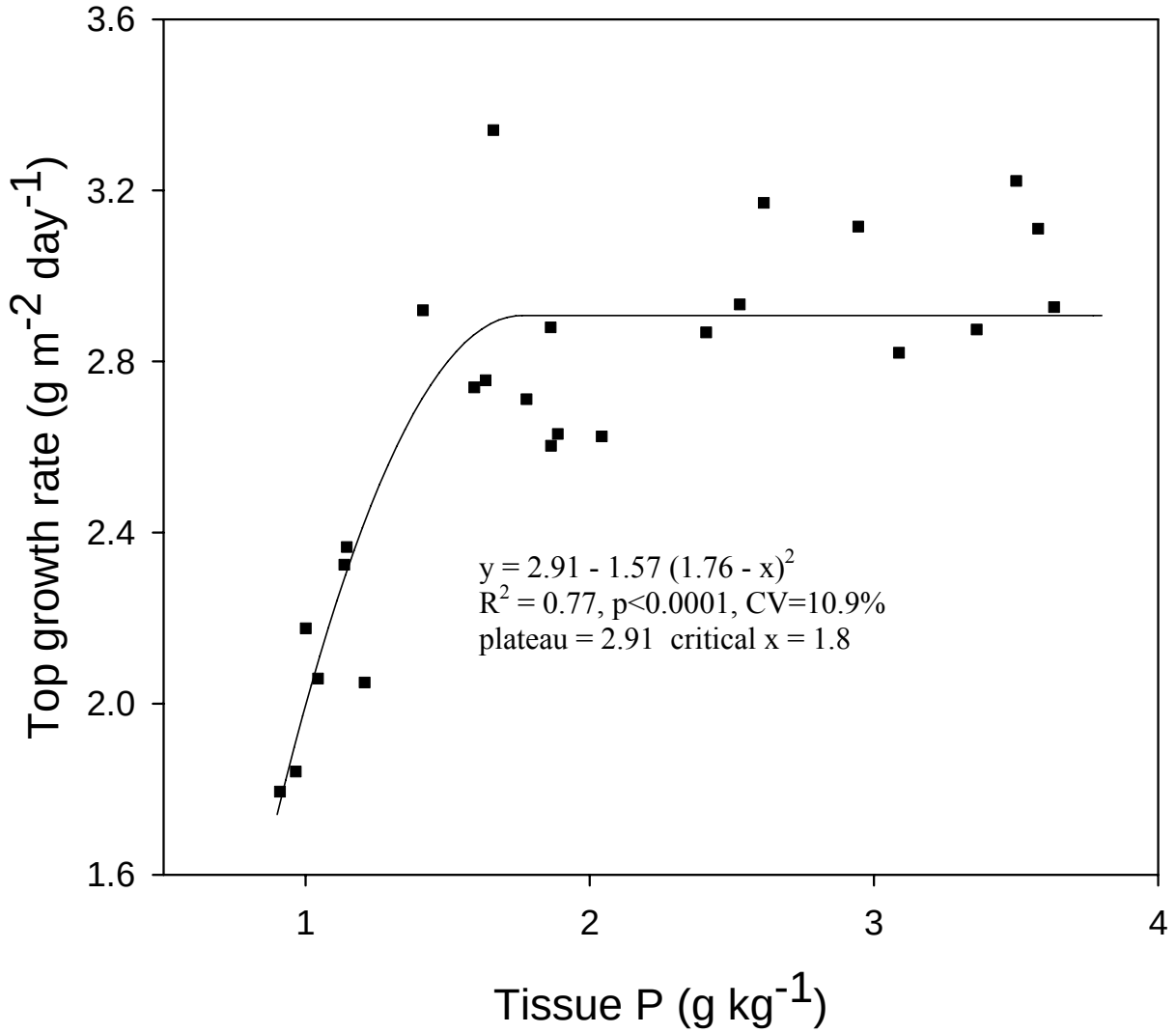

Figure 4-8. St. Augustinegrass tissue growth rate relative to tissue P concentration in the glasshouse soil study 1.

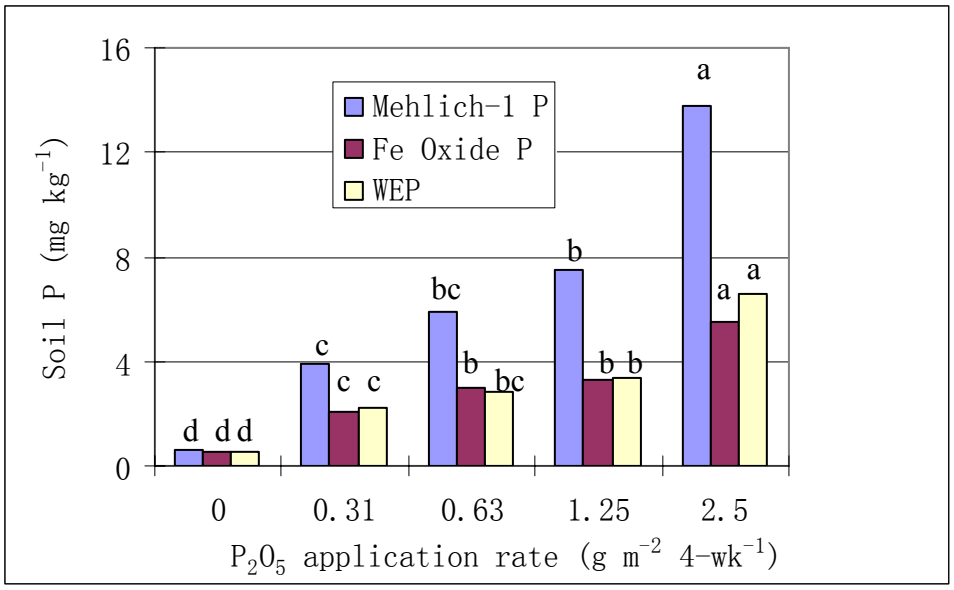

Figure 4-9. Soil Mehlich-1 P, Fe Oxide P, and WEP concentration as influenced by P application rate (soil sampling depth of 0-2 cm) in the glasshouse soil study 1.

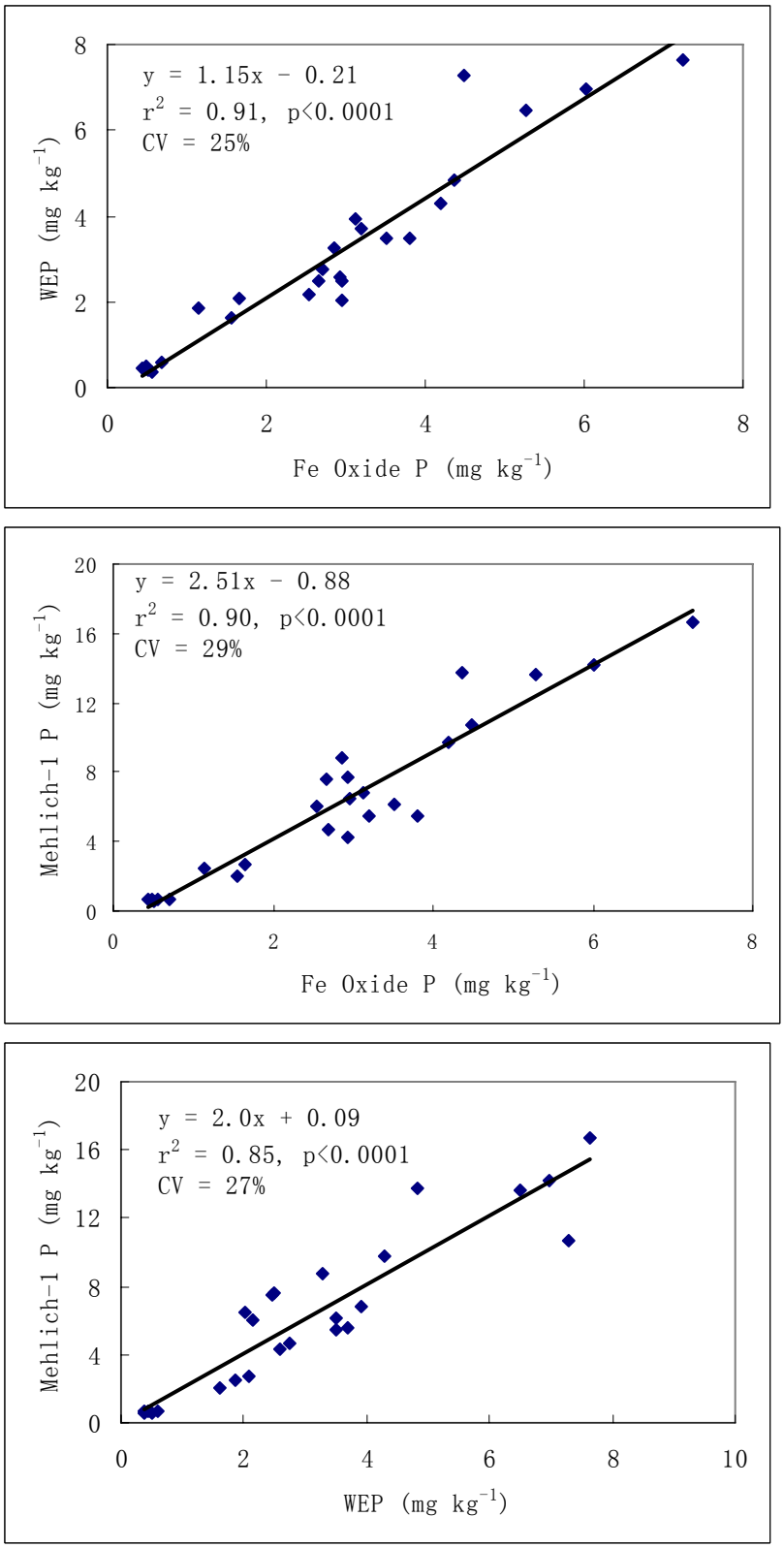

Figure 4-10. Relationships among Mehlich-1 P, Fe Oxide P, and WEP concentrations (soils sampling depth of 0-2 cm) in the glasshouse soil study 1.

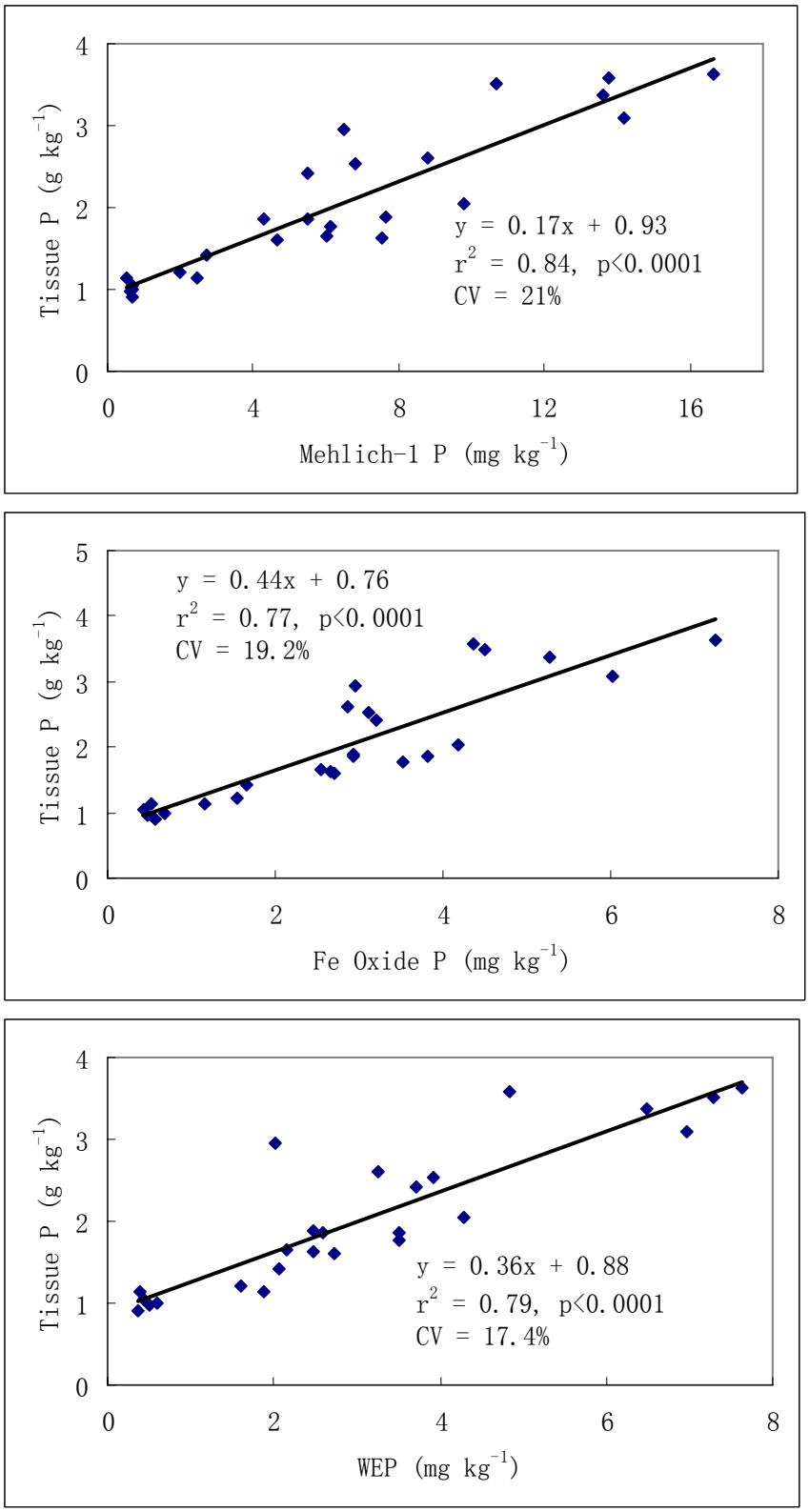

Figure 4-11. Relationships between tissue P concentration and Mehlich-1 P, Fe Oxide P, and WEP concentrations (soils sampling depth of 0-2 cm) in the glasshouse soil study 1.

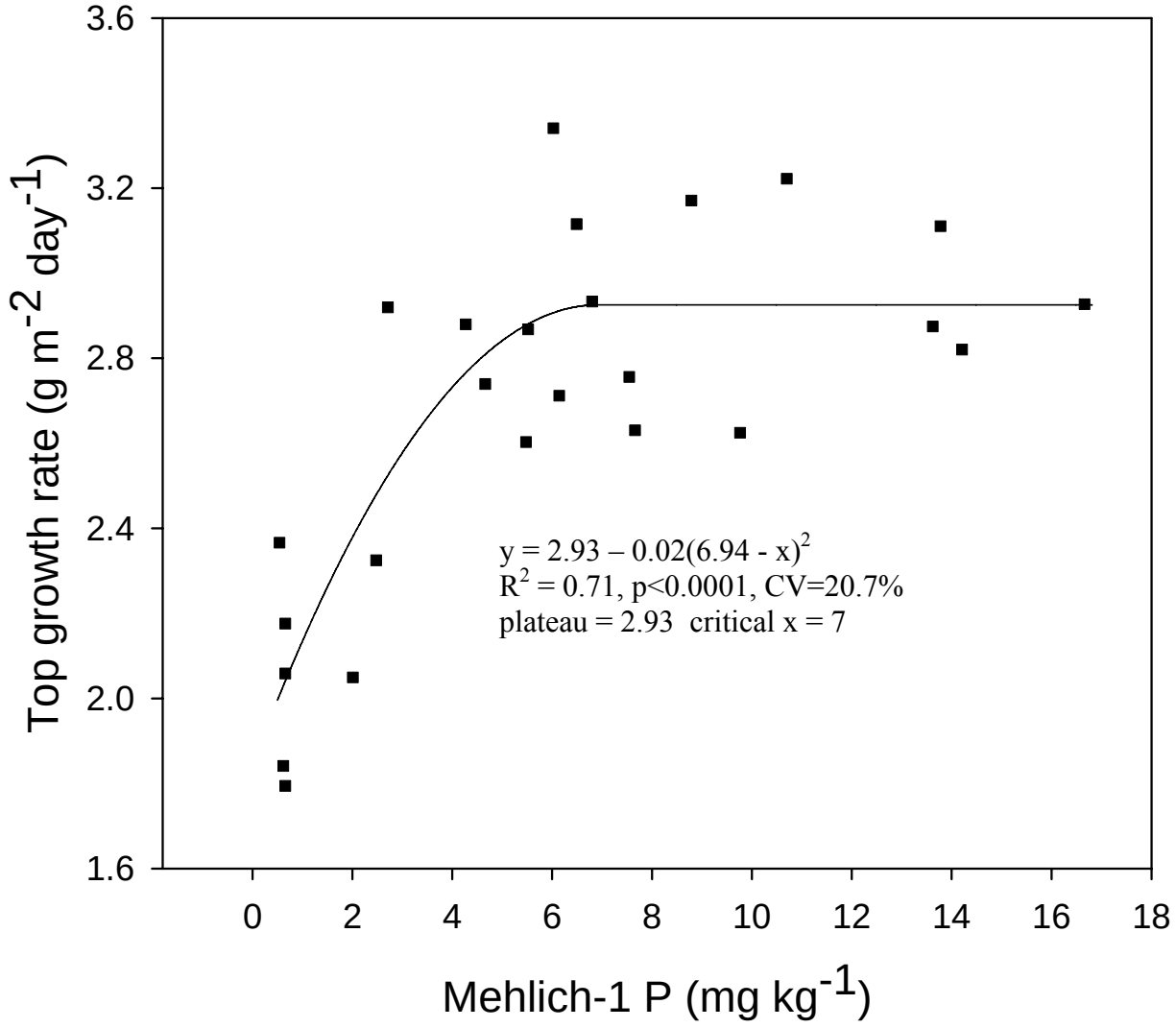

Figure 4-12. St. Augustinegrass tissue growth rate relative to soil Mehlich-1 P concentration in the glasshouse soil study 1.

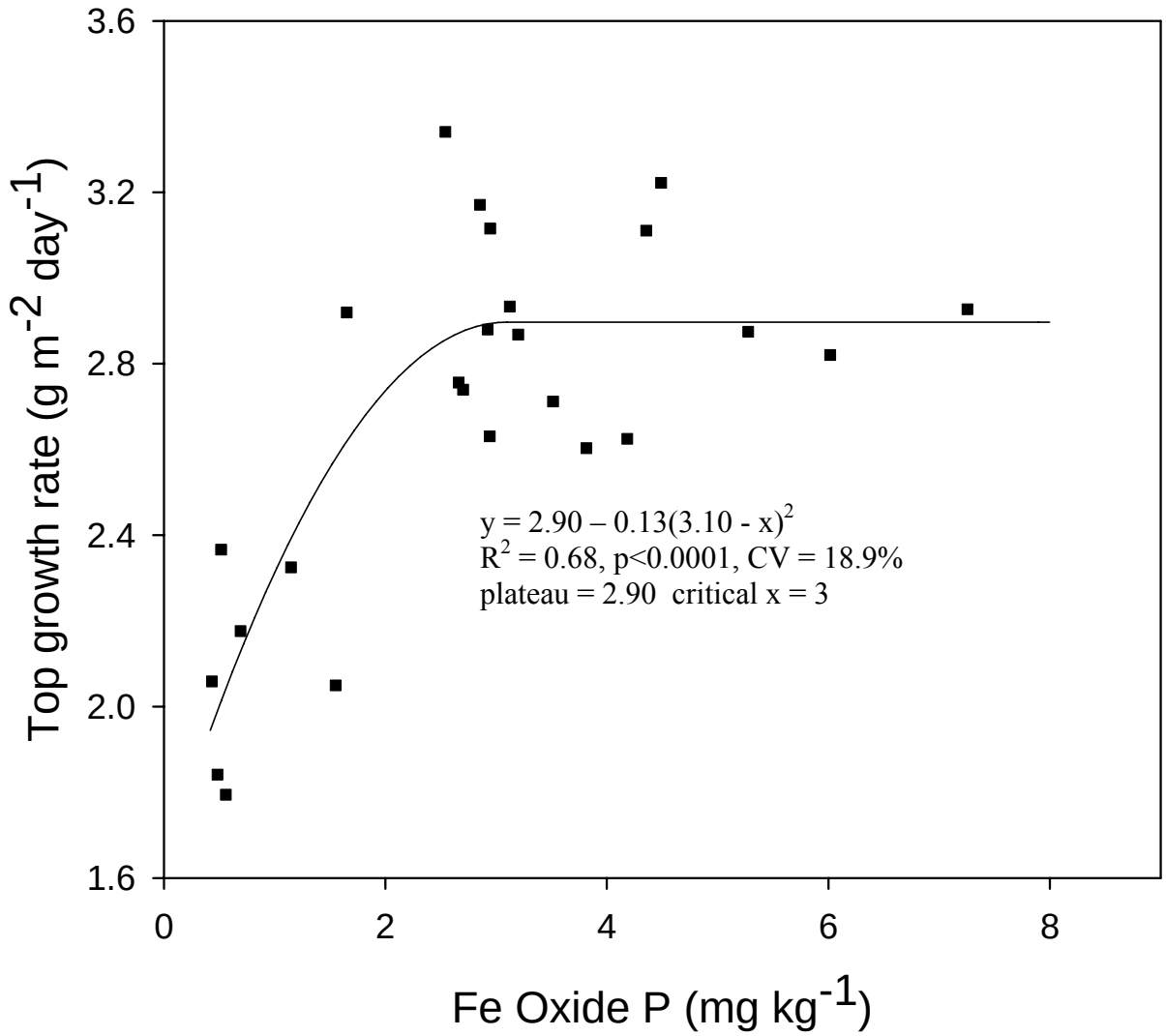

Figure 4-13. St. Augustinegrass tissue growth rate relative to soil Fe Oxide P concentration in the glasshouse soil study 1.

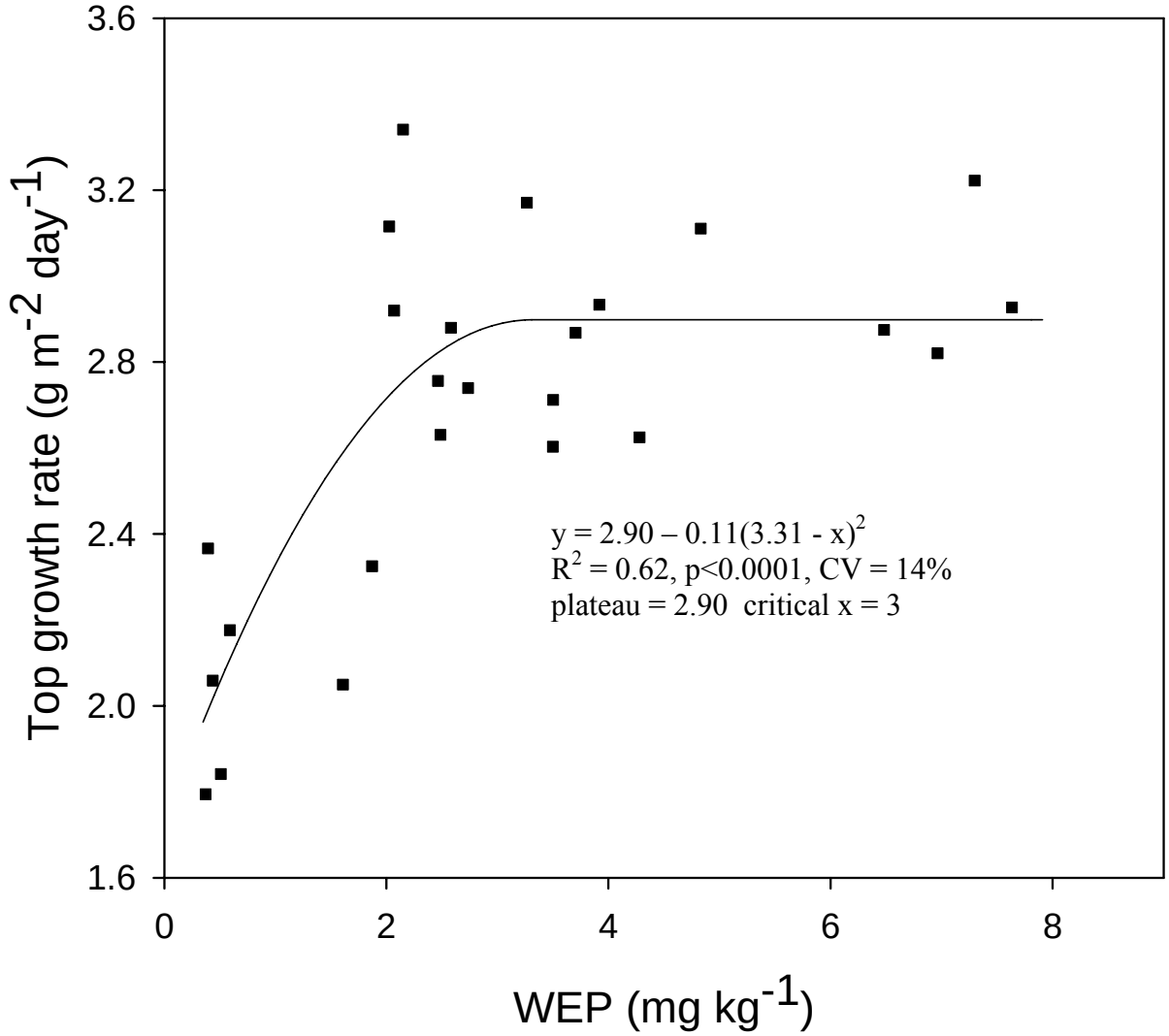

Figure 4-14. St. Augustinegrass tissue growth rate relative to soil WEP concentration in the glasshouse soil study 1.

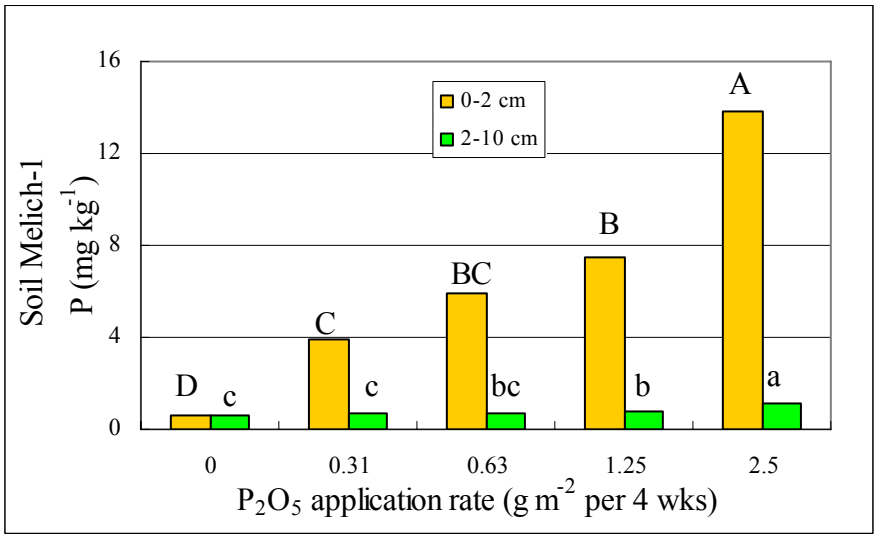

Figure 4-15. Soil Mehlich-1 P concentration as influenced by P application rate and soil sampling depth in the glasshouse soil study 1.

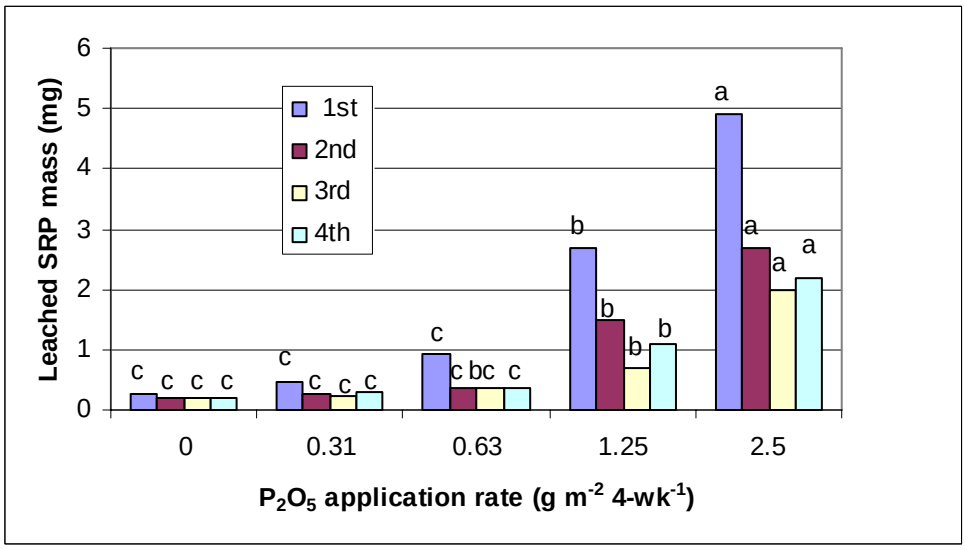

Figure 4-16. Leached SRP mass as influenced by P application rate and leaching event in glasshouse soil study 1.

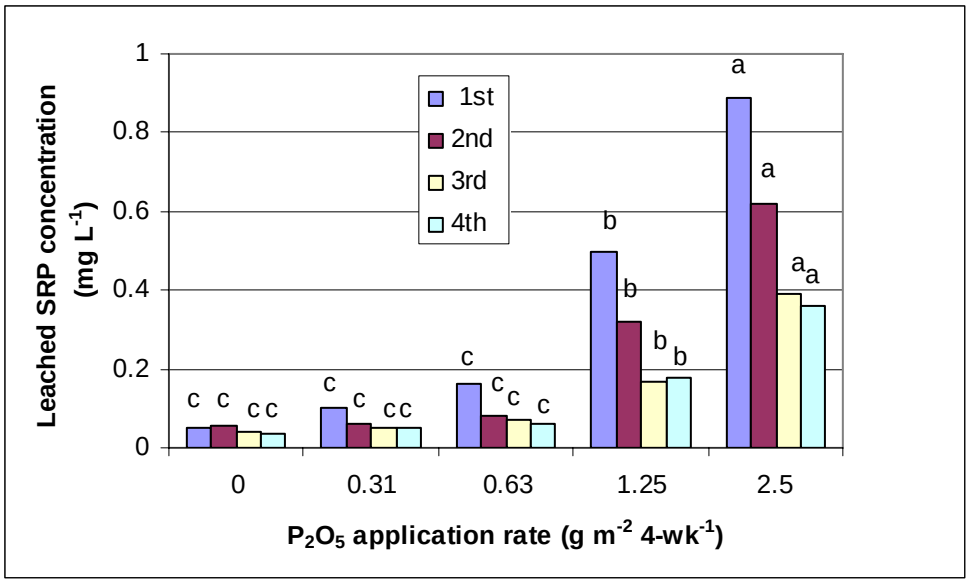

Figure 4-17. Leached SRP concentration as influenced by P application rate and leaching event in glasshouse soil study 1.

Table 4-4. Visual quality rating of St. Augustinegrass as influenced by P application rate in 2005–2006 glasshouse soil study 2.

Soil	P_2O_5 rates ($g\ m^{-2}\ 4\text{-}wk^{-1}$)	Week† 1	2	3	4	5	6	7	8	9	10	11	12	Mean
2	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
	0.31	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
	0.63	6.9a	7.6ab	7.3a	7.4a	7.2a	7.5a	6.8a	7.1a	7.3ab	7.6a	6.6a	7.0a	7.2a
	1.25	7.3a	8.1a	7.3a	7.6a	7.4a	7.7a	7.1a	7.2ab	7.3ab	8.0a	7.0a	7.1a	7.4a
	2.5	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
3	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
	0.31	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
	0.63	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
	1.25	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
	2.5	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	8.0	9.1	6.7	10.7	9.9	10.6	6.8	8.6	6.6	10.1	7.5	6.3

†Within columns for each soil, means followed by the same letter are not significantly different according to Tukey's test (0.05).

Table 4-5. Top growth rate of St. Augustinegrass as influenced by P application rate and soils in 2005–2006 glasshouse soil study 2.

Soil	P_2O_5 rates ($g\ m^{-2}\ 4\text{-}wk^{-1}$)	Harvest †($g\ m^{-2}\ day^{-1}$) 1	2	3	4	5	6	Mean
	0	2.7a	1.7b	1.6b	1.2b	1.1b	1.7b	1.6b
	0.31	3.5a	2.3ab	2.5a	2.0a	2.4a	2.5ab	2.5a
2	0.63	3.3a	2.4ab	2.9a	2.1a	2.5a	2.8a	2.6a
	1.25	3.8a	2.6a	3.0a	2.3a	2.7a	2.9a	2.9a
	2.5	3.6a	2.7a	3.0a	2.2a	2.8a	3.0a	2.8a
	0	2.5a	1.5b	1.6c	1.3c	1.3b	1.5b	1.6b
	0.31	3.0a	2.0ab	2.1bc	1.6b	2.1ab	2.1ab	2.1ab
3	0.63	2.9a	1.7ab	2.2bc	1.6abc	2.1ab	2.2ab	2.1ab
	1.25	3.2a	2.4a	2.5a	2.1ab	2.5a	2.5a	2.5a
	2.5	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	18.0	14.0

†Within columns for each soil, means followed by the same letter are not significantly different according to Tukey's test (0.05).

Table 4-6. Tissue P concentration of St. Augustinegrass as influenced by P application rate and soils in 2005–2006 glasshouse soil study 2.

Soil	P_2O_5 rates ($g\ m^{-2}\ 4\text{-}wk^{-1}$)	Harvest † ($g\ kg^{-1}$) 1	2	3	4	5	6	Mean
	0	1.1d	0.98c	0.94c	0.94c	1.1d	0.89c	0.98d
	0.31	1.3cd	1.2c	1.2c	1.3c	1.4cd	1.3c	1.3cd
2	0.63	1.5c	1.4bc	1.4c	1.4abc	1.9c	1.6bc	1.5c
	1.25	2.0b	1.8b	2.3b	2.2ab	2.9b	2.1b	2.2b
	2.5	3.1a	2.7a	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
	0.31	1.2c	1.0c	1.1c	1.0c	1.4cd	1.2c	1.2c
3	0.63	1.5c	1.2bc	1.2bc	1.3bc	1.9c	1.5c	1.4c
	1.25	2.0b	1.7b	1.8b	1.9b	2.6b	2.2b	2.0b
	2.5	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

†Within columns for each soil, means followed by the same letter are not significantly different according to Tukey's test (0.05).

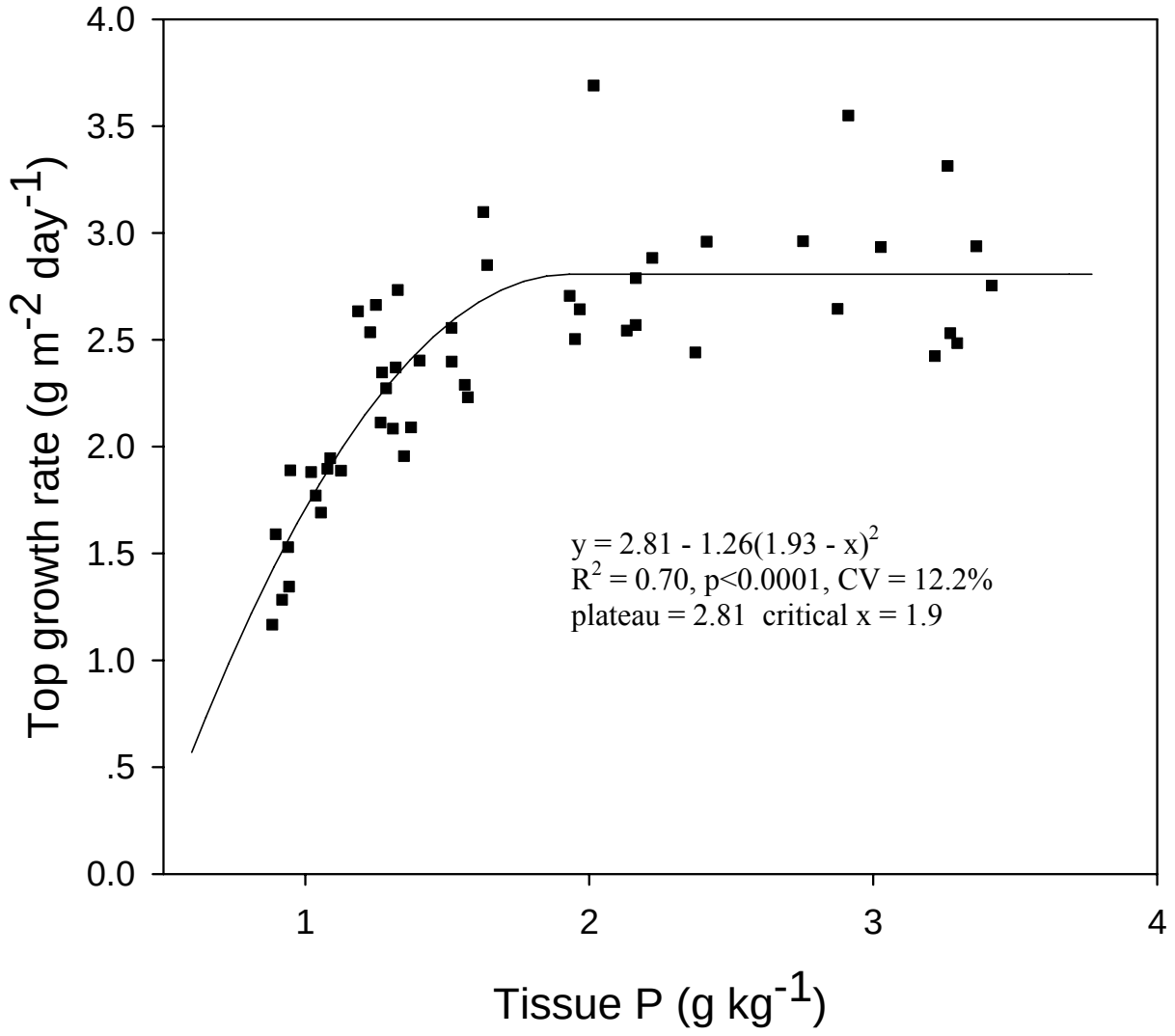

Figure 4-18. St. Augustinegrass tissue growth rate relative to tissue P concentration in the glasshouse soil study 2.

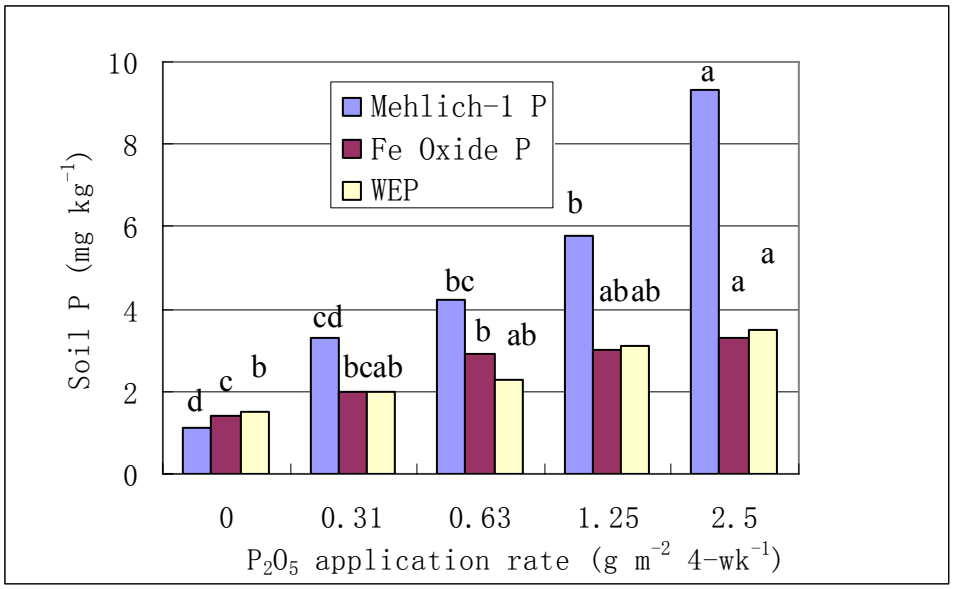

Figure 4-19. Soil Mehlich-1 P, FeO P, and WEP concentration as influenced by P application rate (soil sampling depth of 0-2 cm) in the glasshouse soil study 2 (soil No. 2).

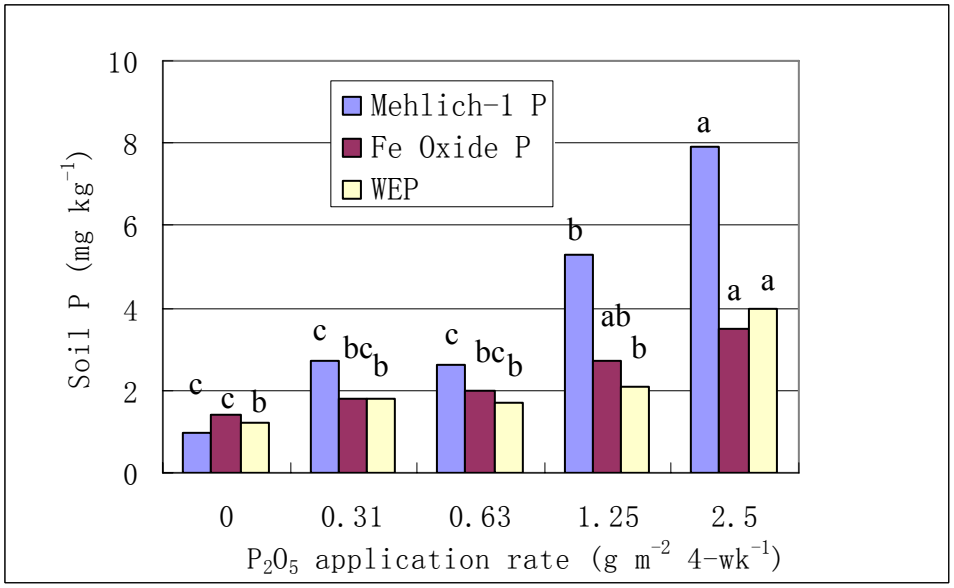

Figure 4-20. Soil Mehlich-1 P, FeO P, and WEP concentration as influenced by P application rate (soil sampling depth of 0-2 cm) in the glasshouse soil study 2 (soil No. 3).

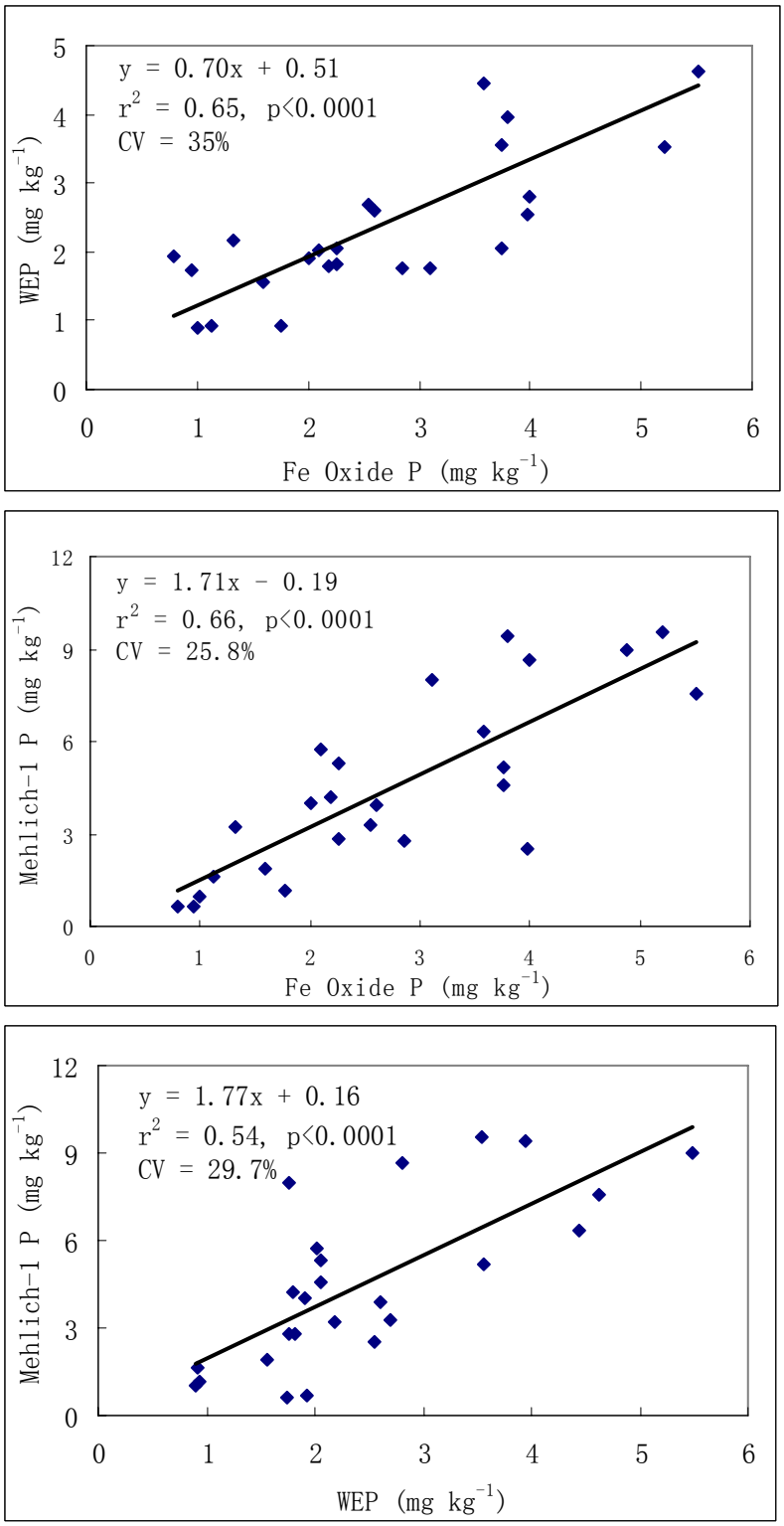

Figure 4-21. Relationships among Mehlich-1 P, Fe Oxide P, and WEP concentrations (soils sampling depth of 0-2 cm) in the glasshouse soil study 2 (soil No. 2).

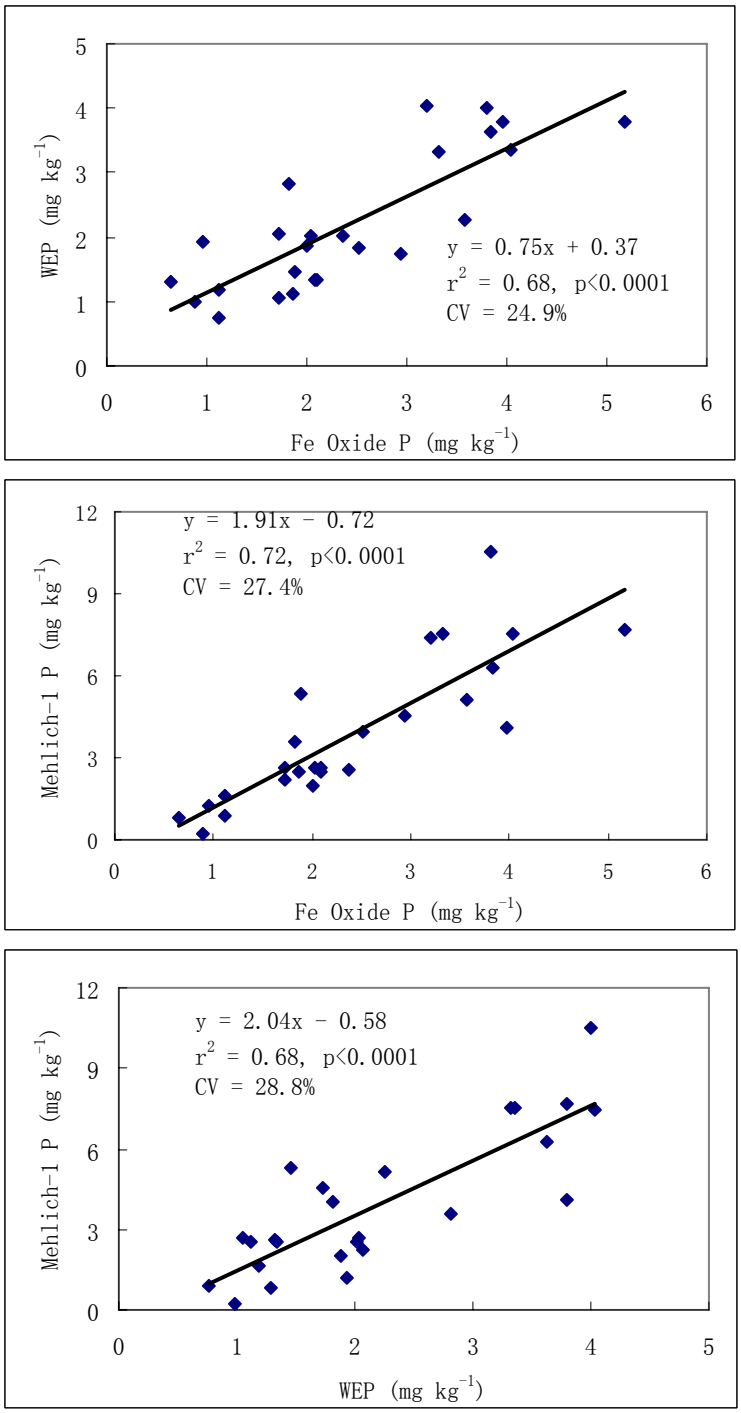

Figure 4-22. Relationships among Mehlich-1 P, Fe Oxide P, and WEP concentrations (soils sampling depth of 0-2 cm) in the glasshouse soil study 2 (soil No. 3).

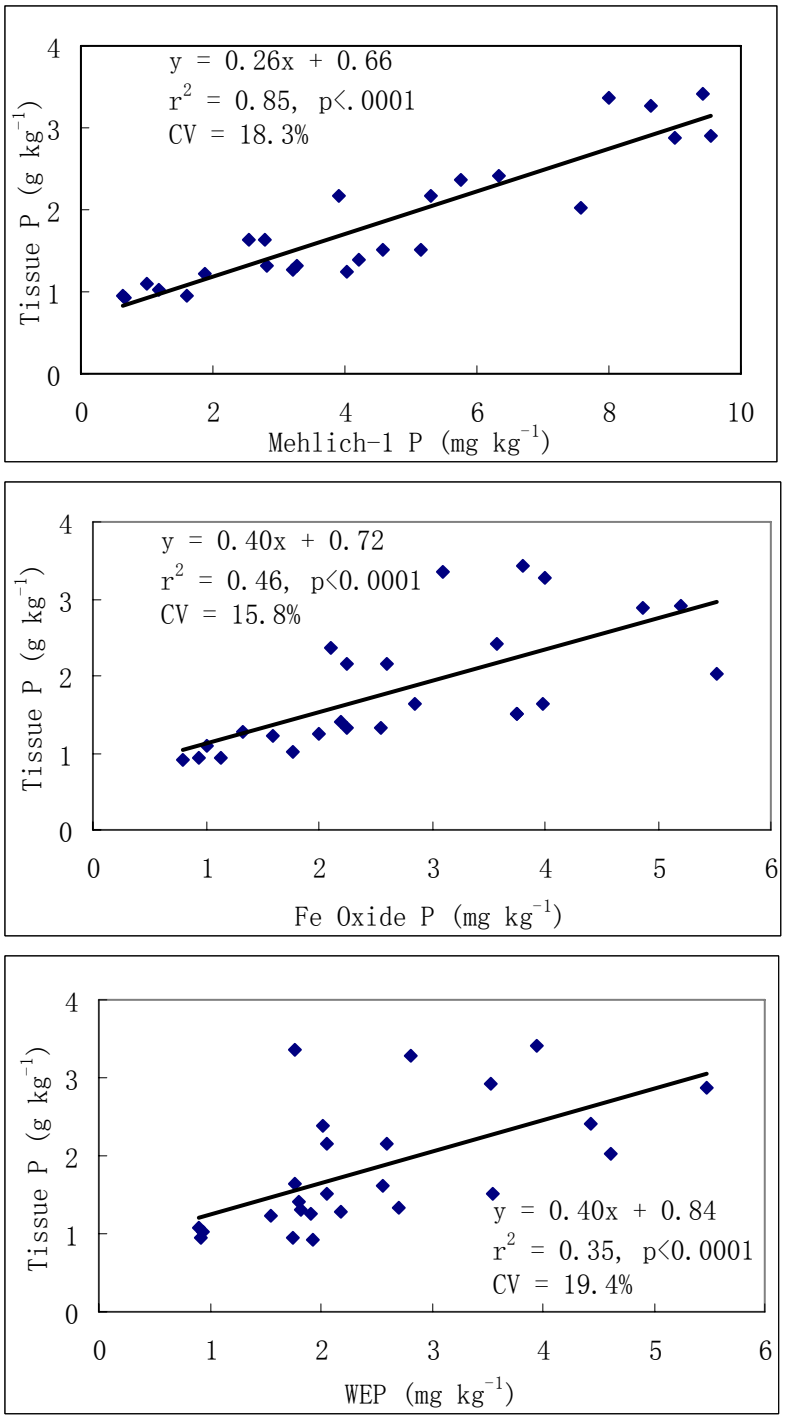

Figure 4-23. Relationships between tissue P concentration and Mehlich-1 P, Fe Oxide P, and WEP concentrations (soils sampling depth of 0–2 cm) in the glasshouse soil study 2 (soil No. 2).

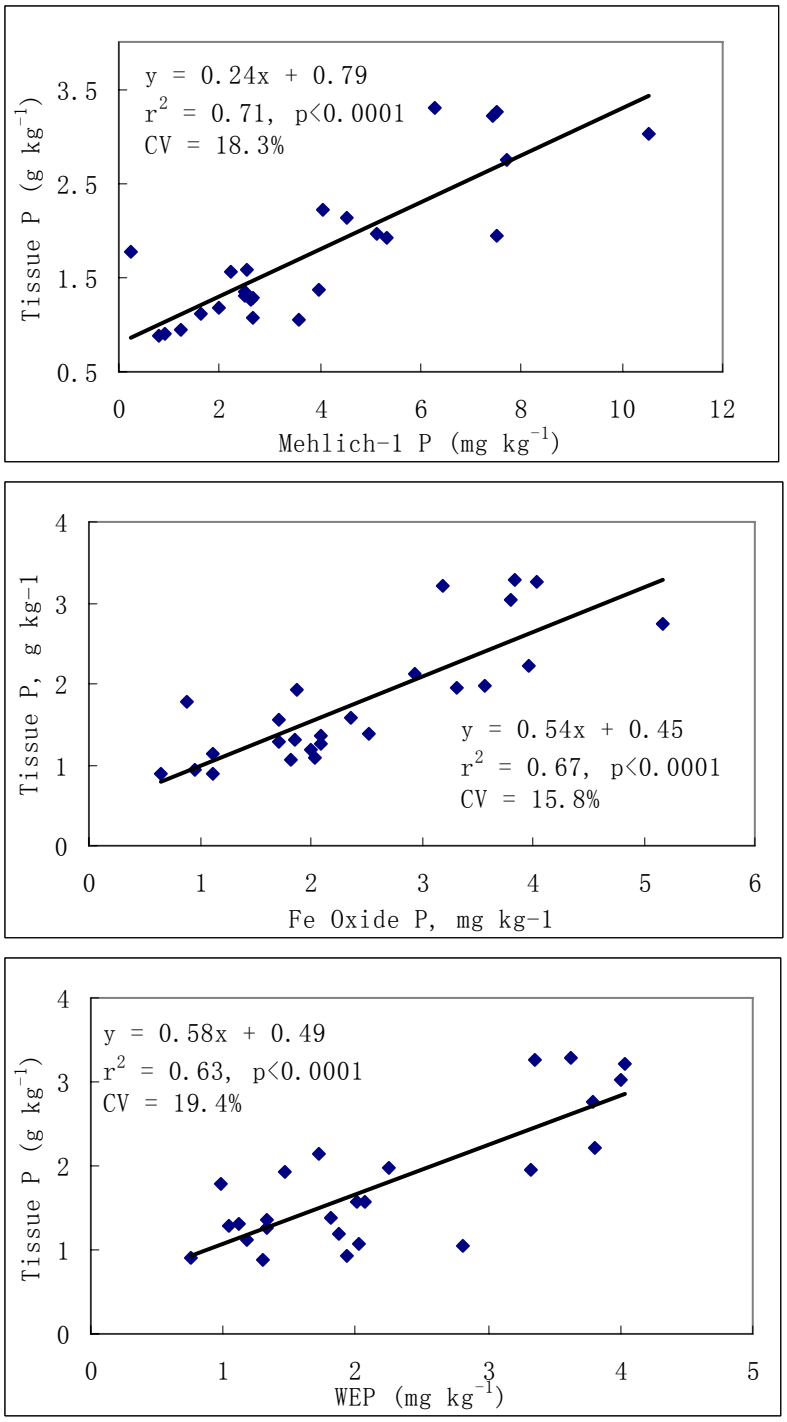

Figure 4-24. Relationships between tissue P concentration and Mehlich-1 P, Fe Oxide P, and WEP concentrations (soils sampling depth of 0–2 cm) in the glasshouse soil study 2 (soil No. 3).

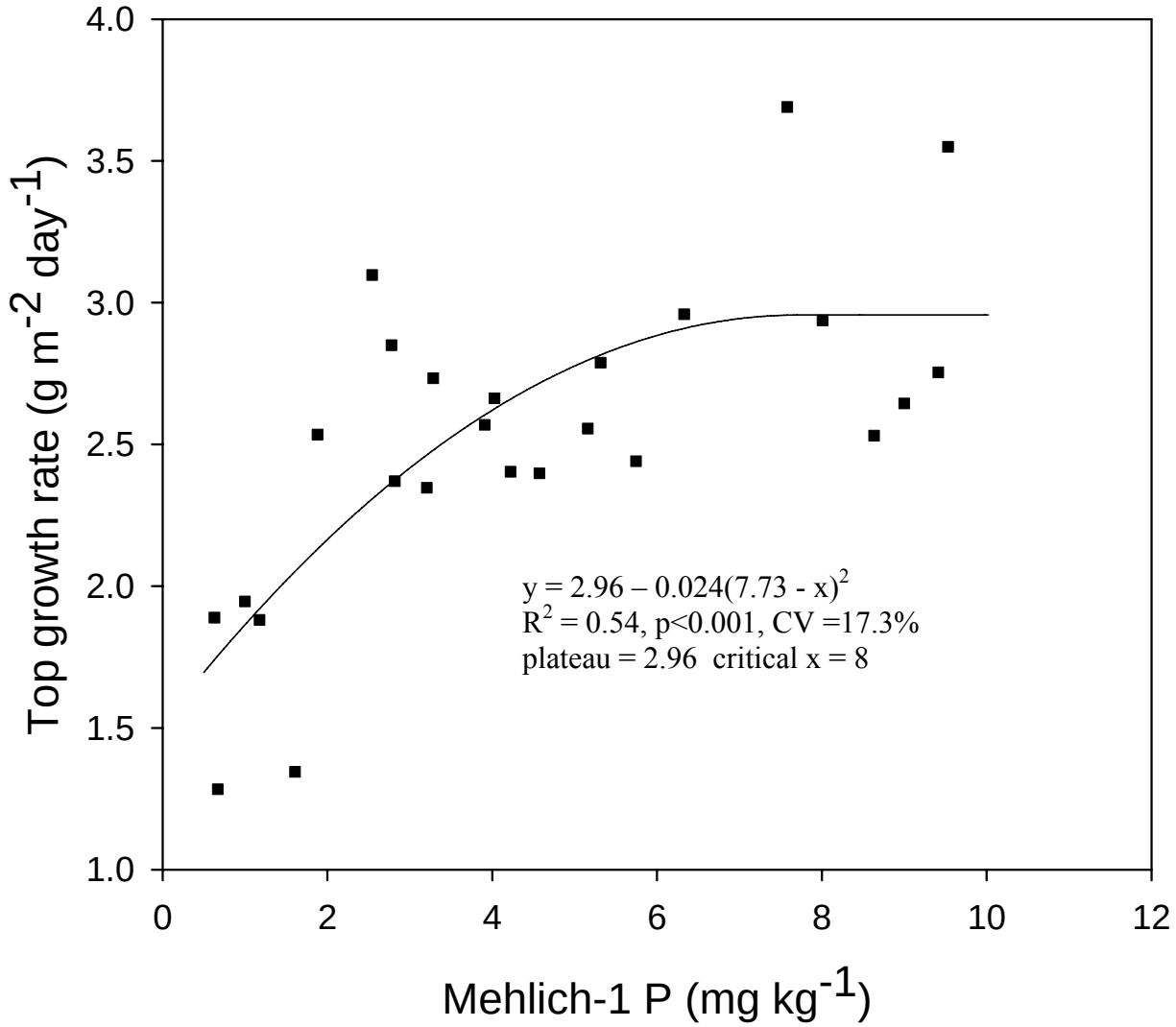

Figure 4-25. St. Augustinegrass tissue growth rate relative to soil Mehlich-1 P concentration in the glasshouse soil study 2 (soil No. 2).

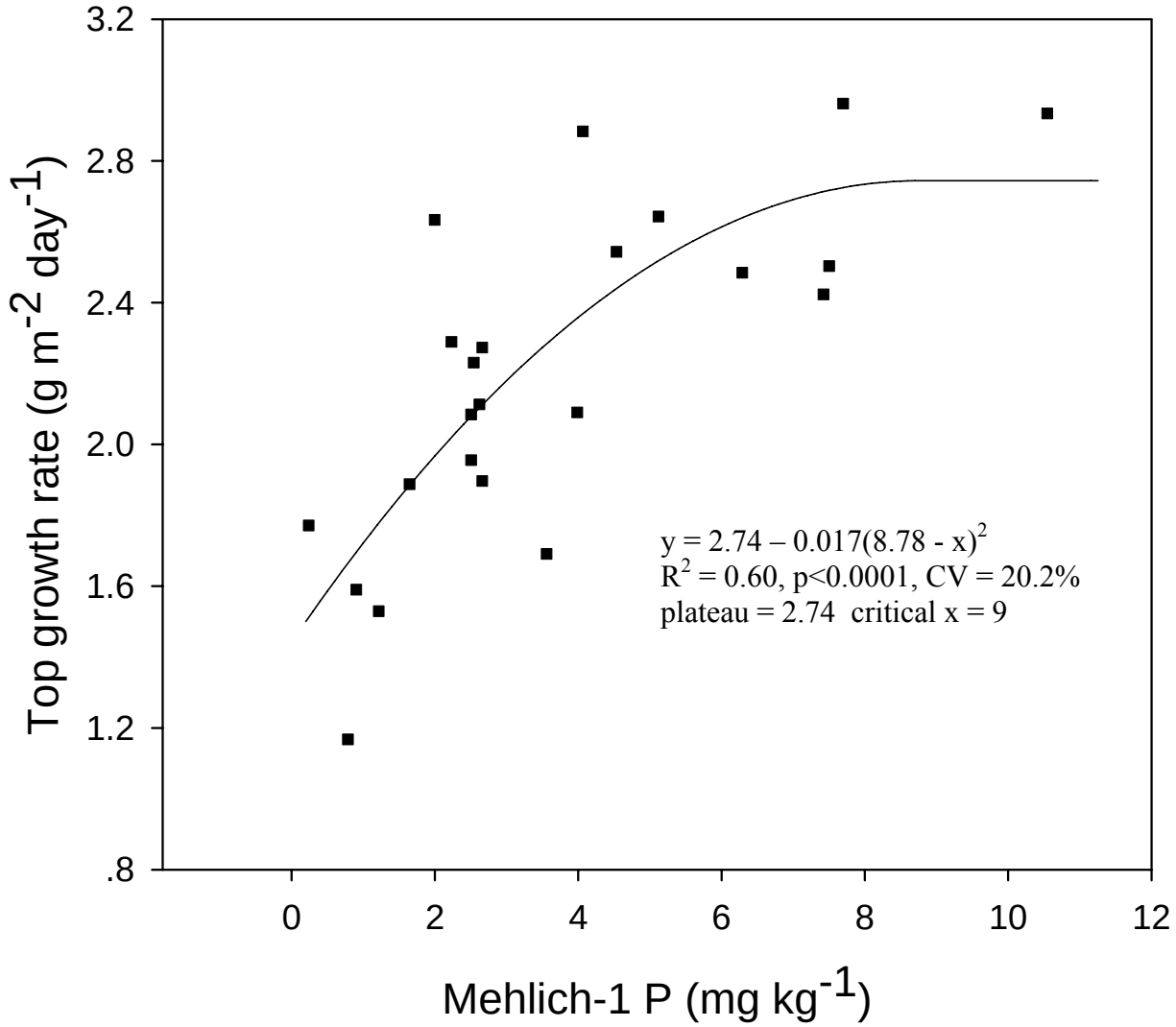

Figure 4-26. St. Augustinegrass tissue growth rate relative to soil Mehlich-1 P concentration in the glasshouse soil study 2 (soil No. 3).

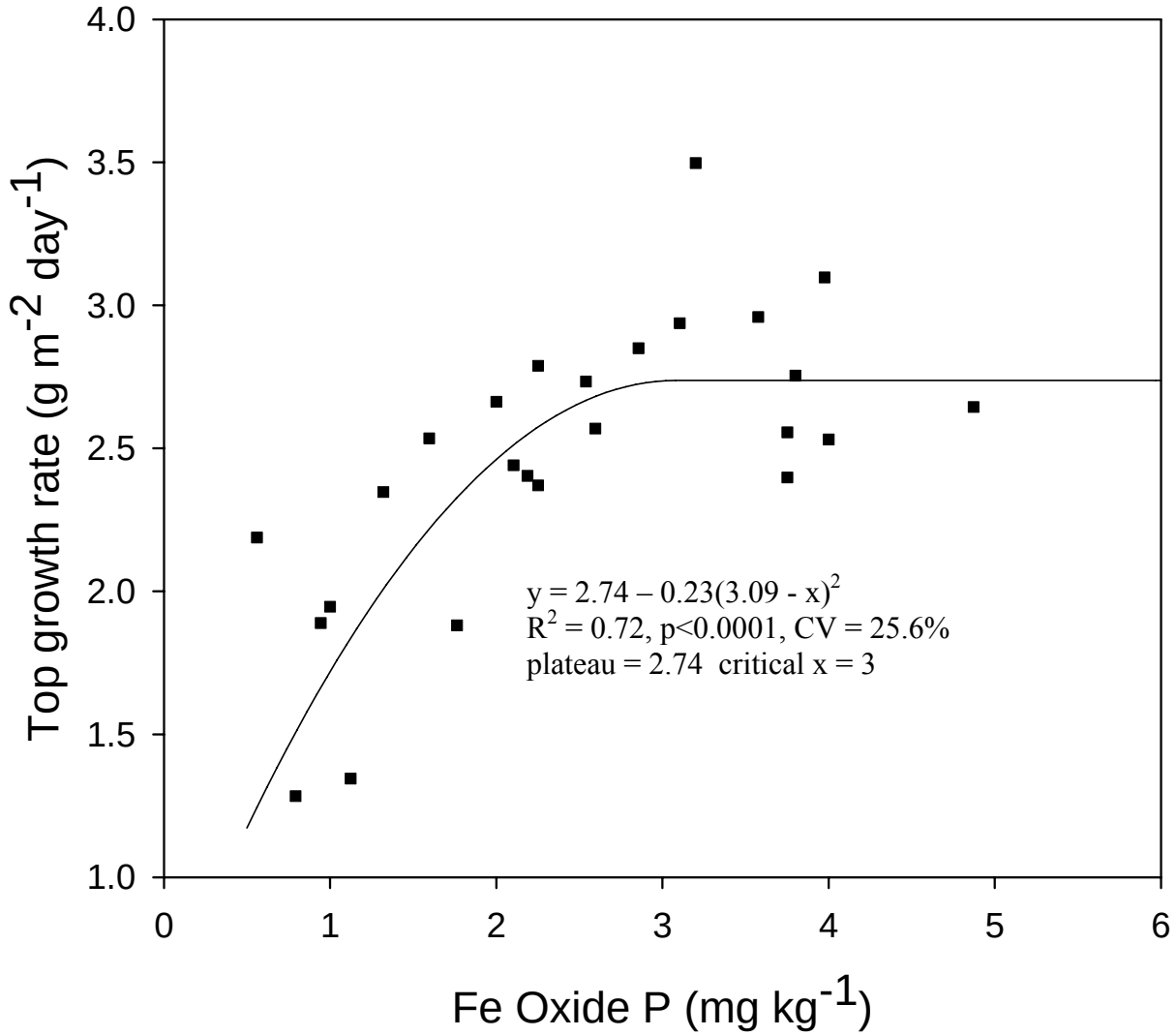

Figure 4-27. St. Augustinegrass tissue growth rate relative to soil Fe Oxide P concentration in the glasshouse soil study 2 (soil No.2).

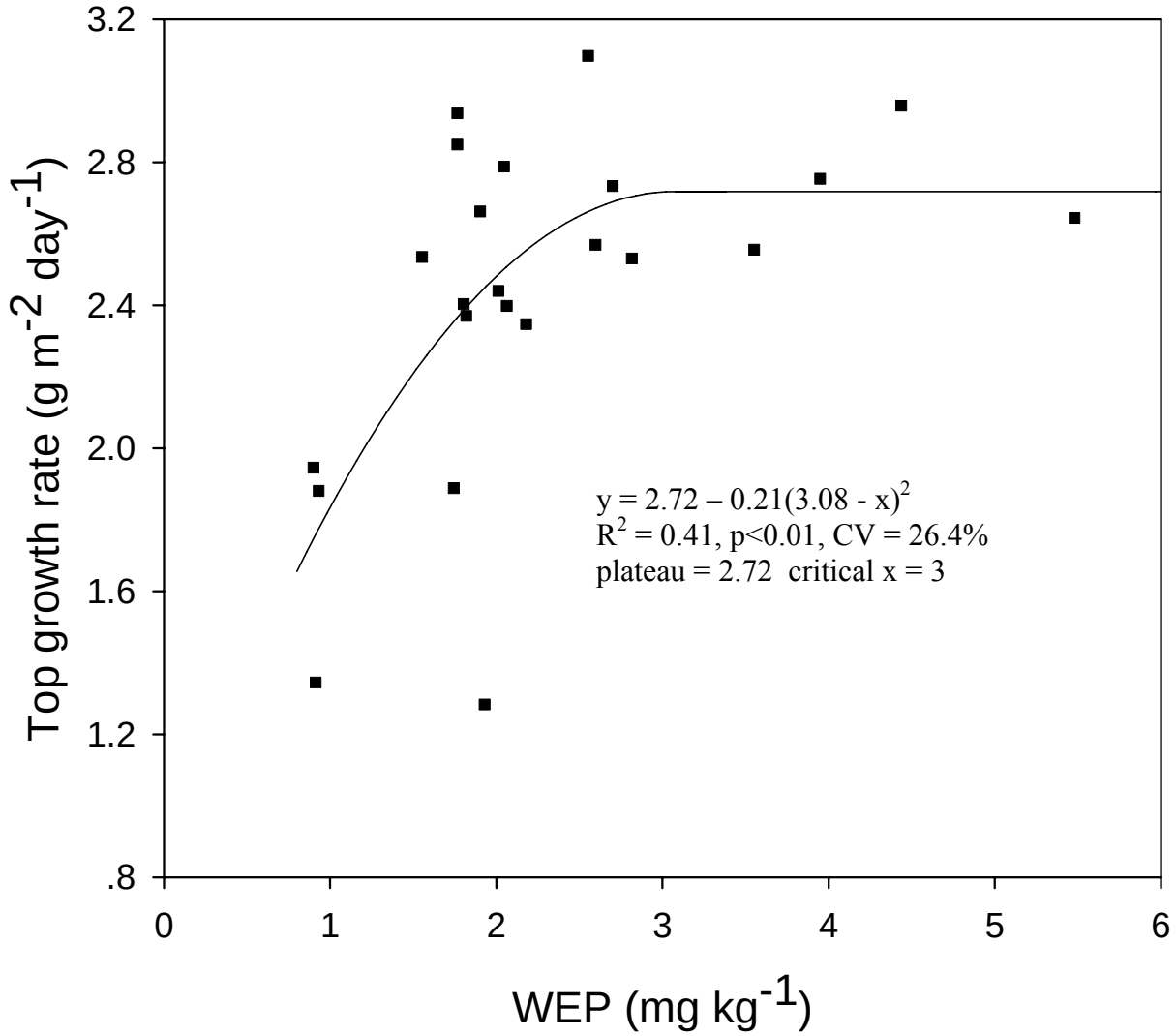

Figure 4-28. St. Augustinegrass tissue growth rate relative to soil WEP concentration in the glasshouse soil study 2 (soil No.2).

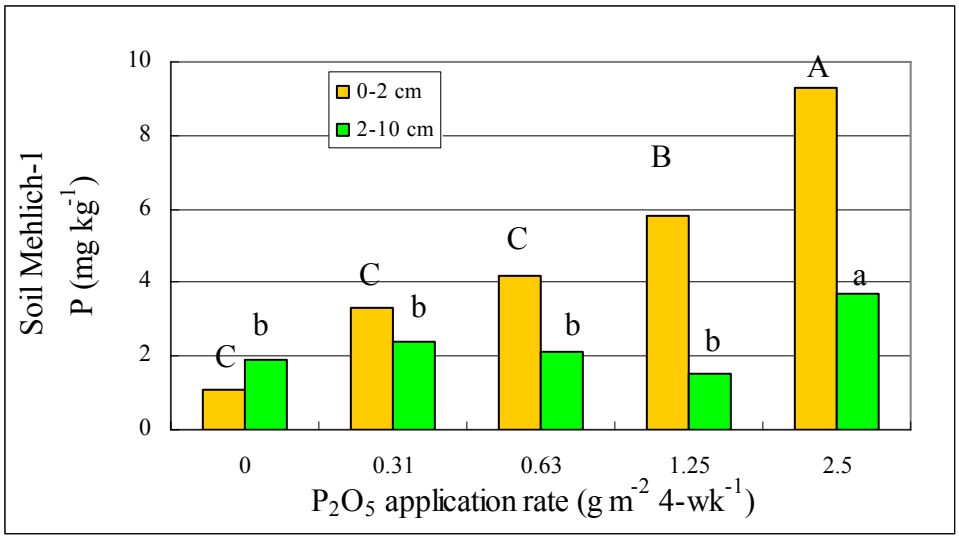

Figure 4-29. Soil Mehlich-1 P concentration as influenced by P application rate and soil sampling depth in the glasshouse study 2 (soil No. 2).

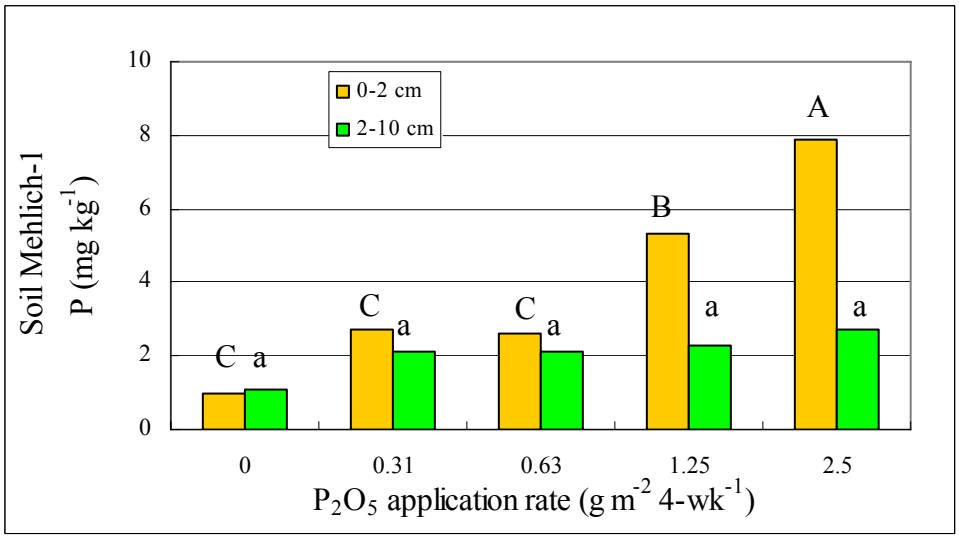

Figure 4-30. Soil Mehlich-1 P concentration as influenced by P application rate and soil sampling depth in the glasshouse study 2 (soil No. 3).

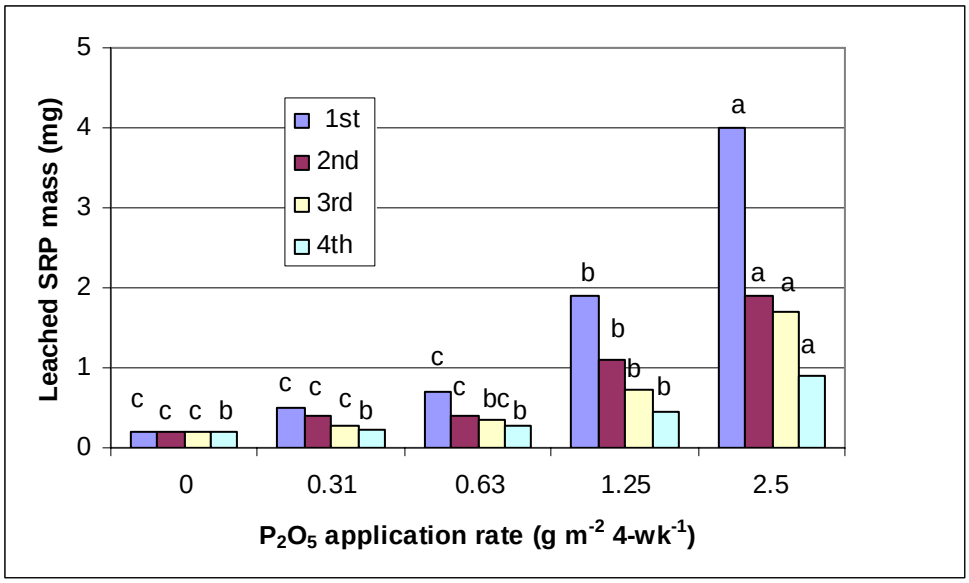

Figure 4-31. Leached SRP mass as influenced by P application rate and leaching event in glasshouse soil study 2 (soil No.2).

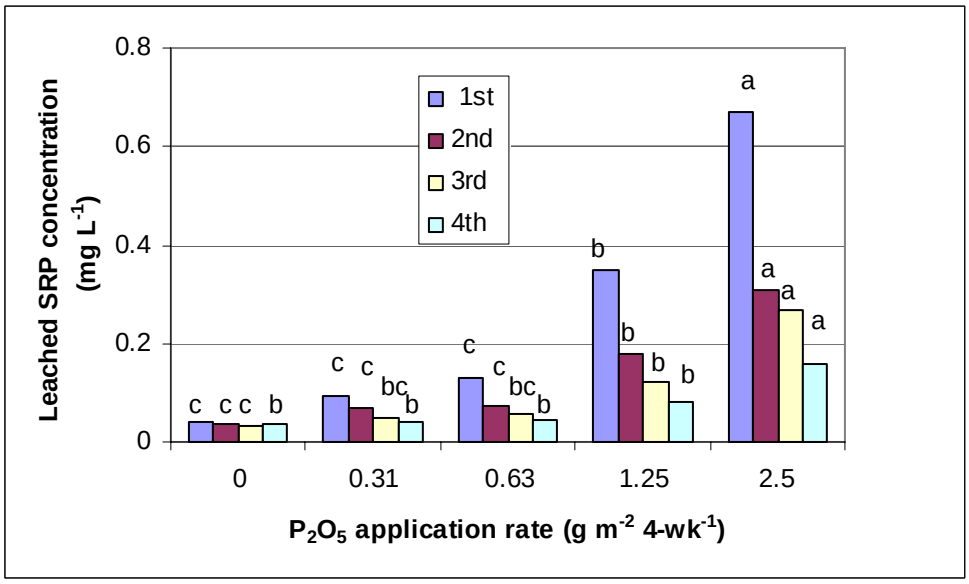

Figure 4-32. Leached SRP concentration as influenced by P application rate and leaching event in glasshouse soil study 2 (soil No.2).

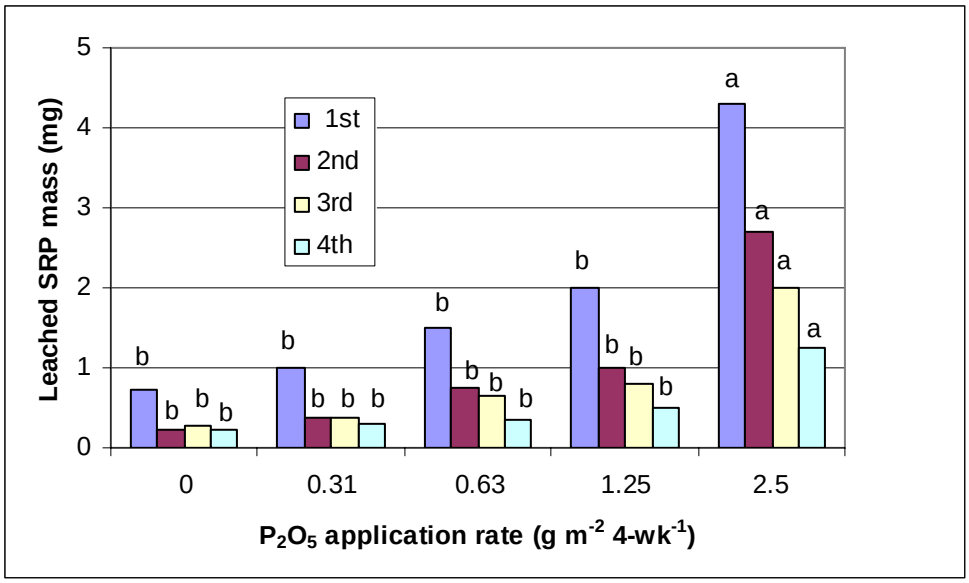

Figure 4-33. Leached SRP mass as influenced by P application rate and leaching event in glasshouse soil study 2 (soil No.3).

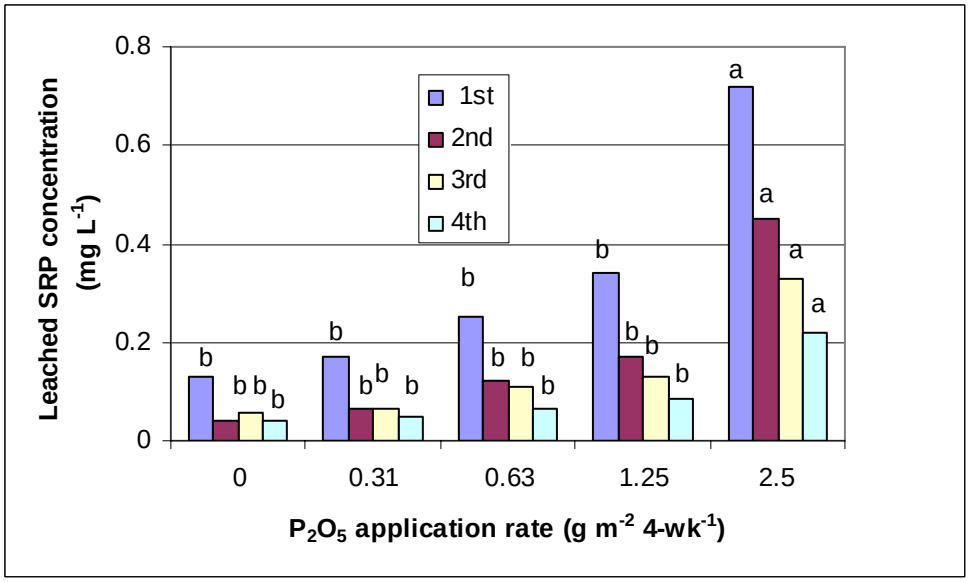

Figure 4-34. Leached SRP concentration as influenced by P application rate and leaching event in glasshouse soil study 2 (soil No.3).

Table 4-7. Visual quality rating of St. Augustinegrass as influenced by P application rate in 2005–2006 glasshouse soil study 3.

P_2O_5 rates	Week †												
(g m^{-2} 4-wk^{-1})	1	2	3	4	5	6	7	8	9	10	11	12	Mean
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
0.31	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
0.63	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
1.25	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
2.5	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	6.54	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 (0.05).

Table 4-8. Top growth rate of St. Augustinegrass as influenced by P application rate in 2005–2006 glasshouse soil study 3.

P_2O_5 rates	Harvest (g m^{-2} day^{-1})						
(g m^{-2} 4-wk^{-1})	1	2	3	4	5	6	Mean
0	3.2b	3.0a	2.8b	1.6b	2.0b	1.5b	2.4b
0.31	3.8ab	3.1a	3.0ab	1.9ab	2.5ab	1.6ab	2.6a
0.63	3.9a	3.1a	3.0ab	2.0 a	2.6a	1.7ab	2.7a
1.25	3.9a	3.3 a	3.1ab	2.1a	2.7a	1.7ab	2.8a
2.5	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	13.0	8.0

Within columns for each soil, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

Table 4-9. Tissue P concentration of St. Augustinegrass as influenced by P application rate in 2005–2006 glasshouse soil study 3.

P_2O_5 rates	Harvest (g kg^{-1})						
(g m^{-2} 4-wk^{-1})	1	2	3	4	5	6	Mean
0	1.3d	1.4b	1.3d	1.2d	1.5d	1.5e	1.4d
0.31	1.4d	1.5b	1.7cd	1.5c	1.8d	1.9d	1.6d
0.63	1.8c	2.1a	1.9bc	1.7c	2.3c	2.5c	2.0c
1.25	2.2b	2.3a	2.3b	2.4b	3.0b	3.5b	2.6b
2.5	2.9a	2.4a	3.4a	3.3a	4.1a	4.6a	3.4a
CV(%)	15.0	20.0	14.3	8.8	14.1	9.4	8.6

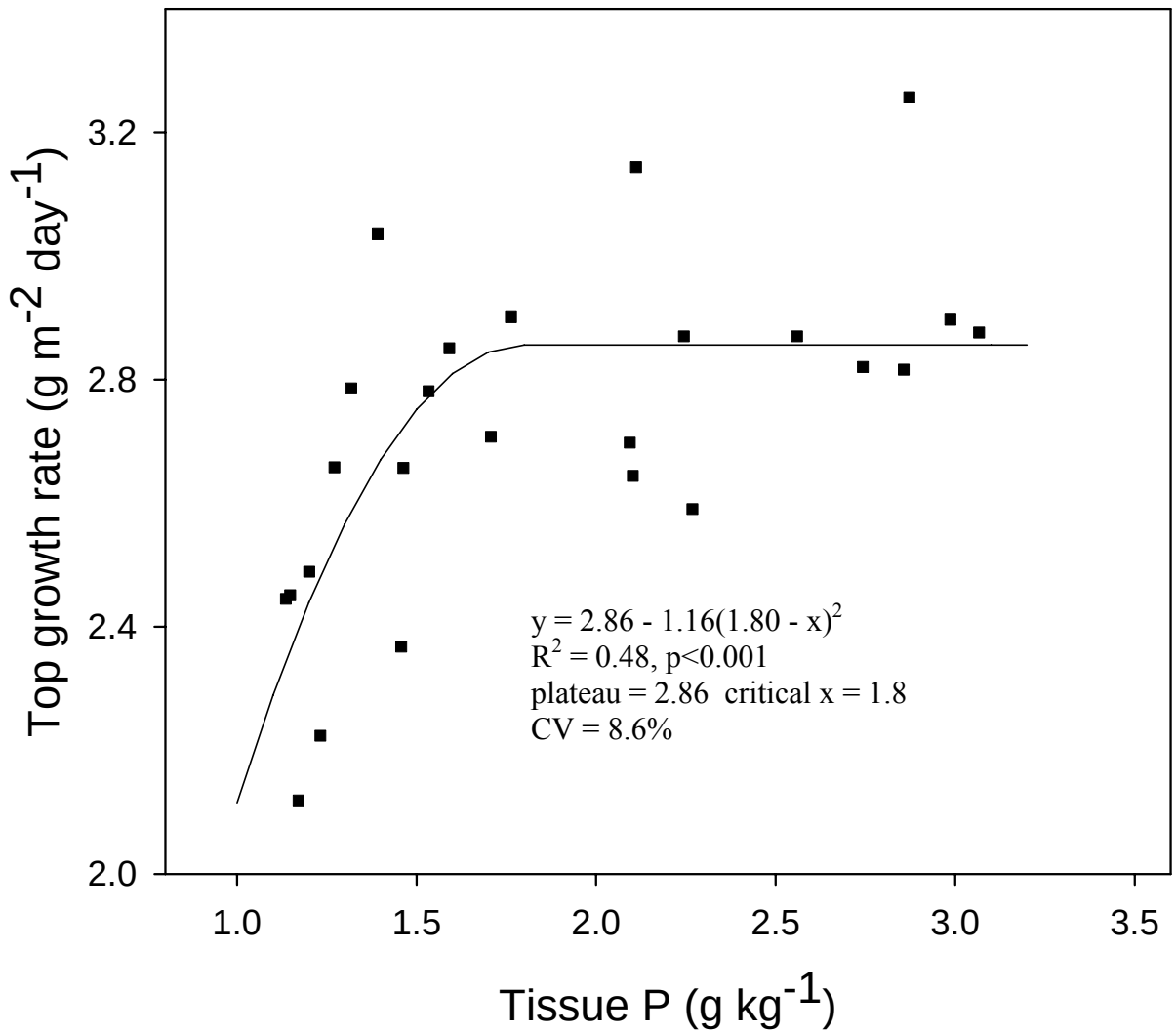

Figure 4-35. St. Augustinegrass tissue growth rate relative to tissue P concentration in the glasshouse soil study 3.

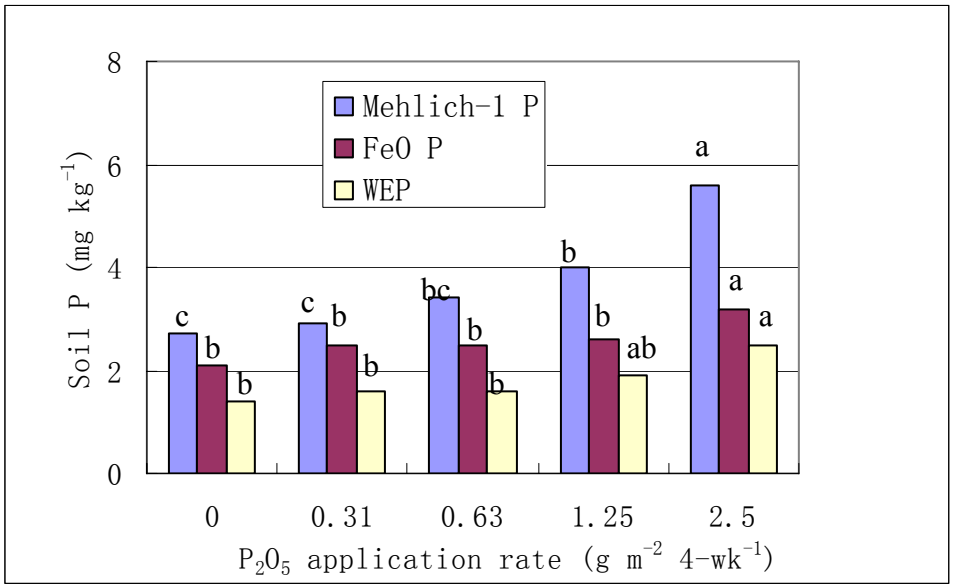

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Figure 4-36. Soil Mehlich-1 P, FeO P, and WEP concentration as influenced by P application rate (soil sampling depth of 0-2 cm) in the glasshouse soil study 3. Within columns for each soil, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

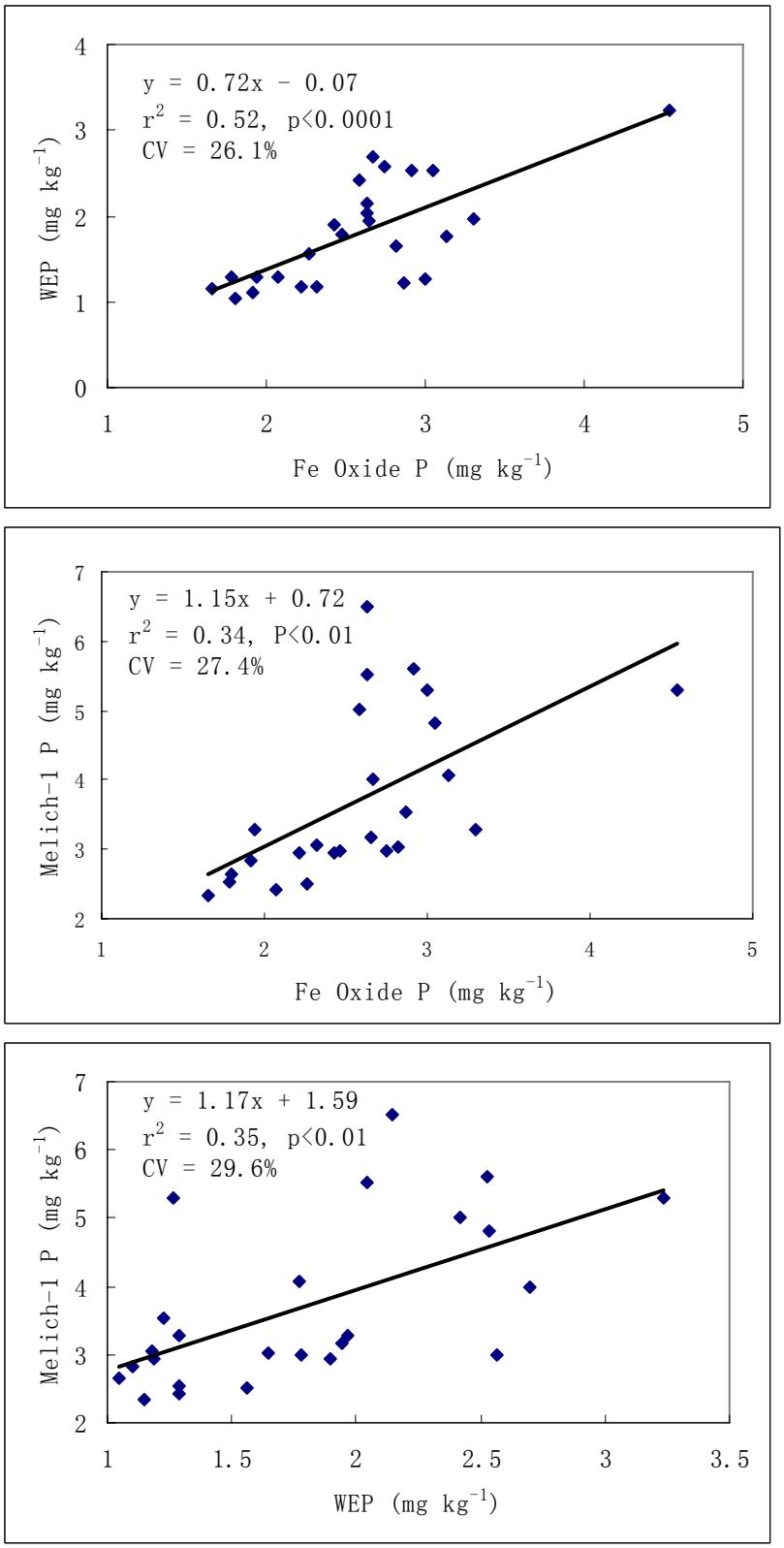

Figure 4-37. Relationships among Mehlich-1 P, Fe Oxide P, and WEP concentrations (soils sampling depth of 0–2 cm) in the glasshouse soil study 3.

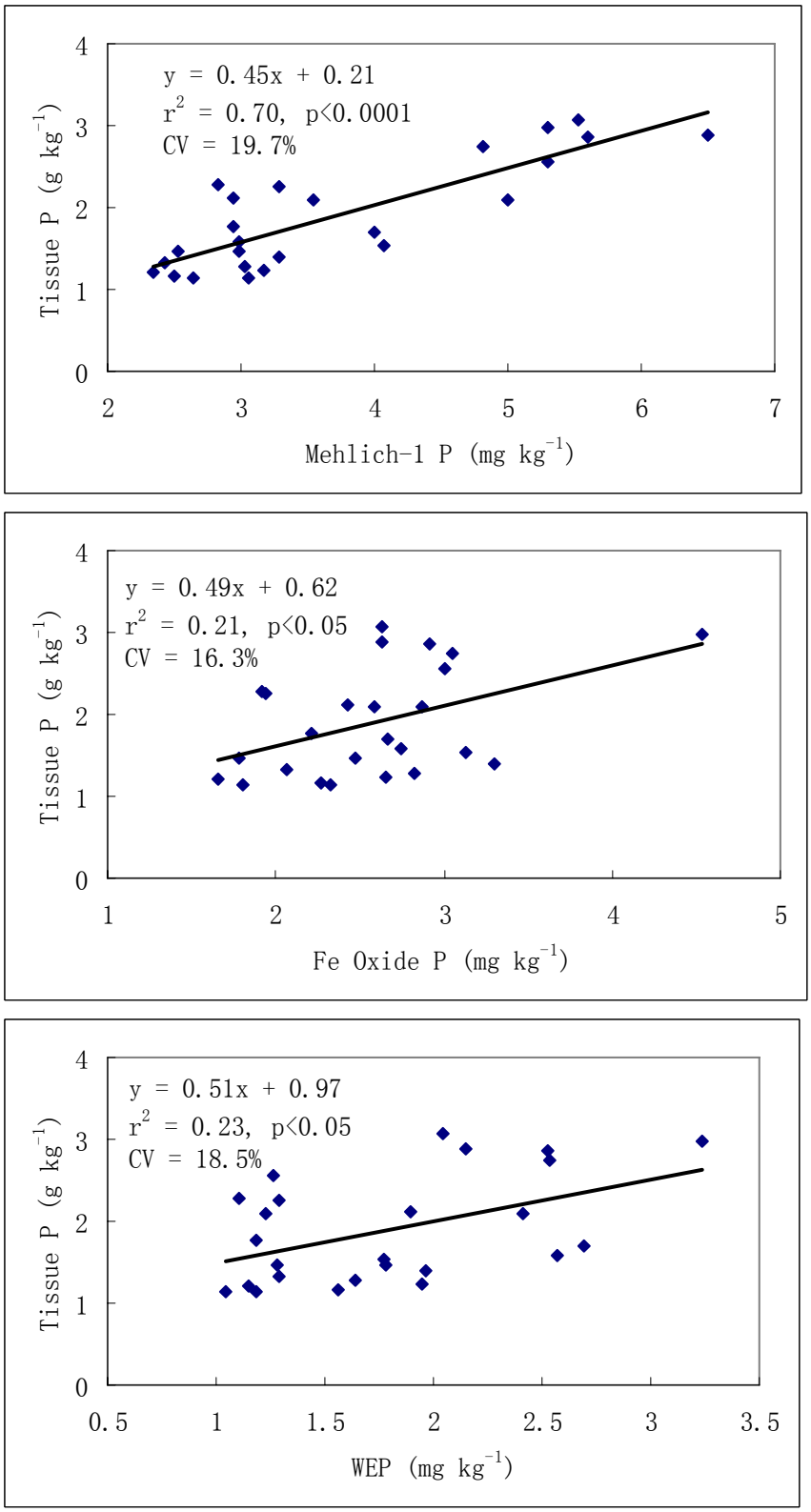

Figure 4-38. Relationships between tissue P concentration and Mehlich-1 P, Fe Oxide P, and WEP concentrations (soils sampling depth of 0–2 cm) in the glasshouse soil study 3.

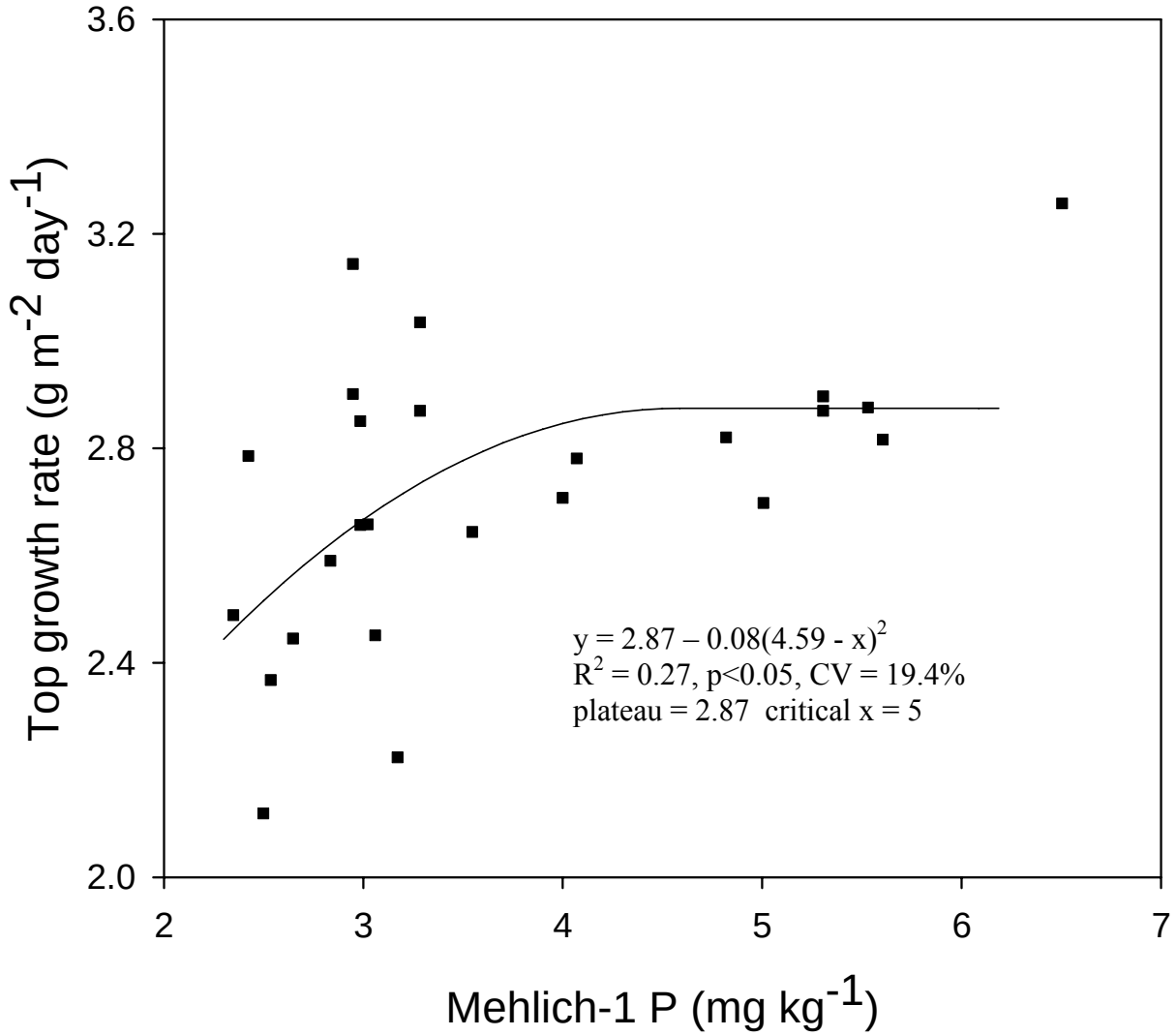

Figure 4-39. St. Augustinegrass tissue growth rate relative to soil Mehlich-1 P concentration in the glasshouse soil study 3.

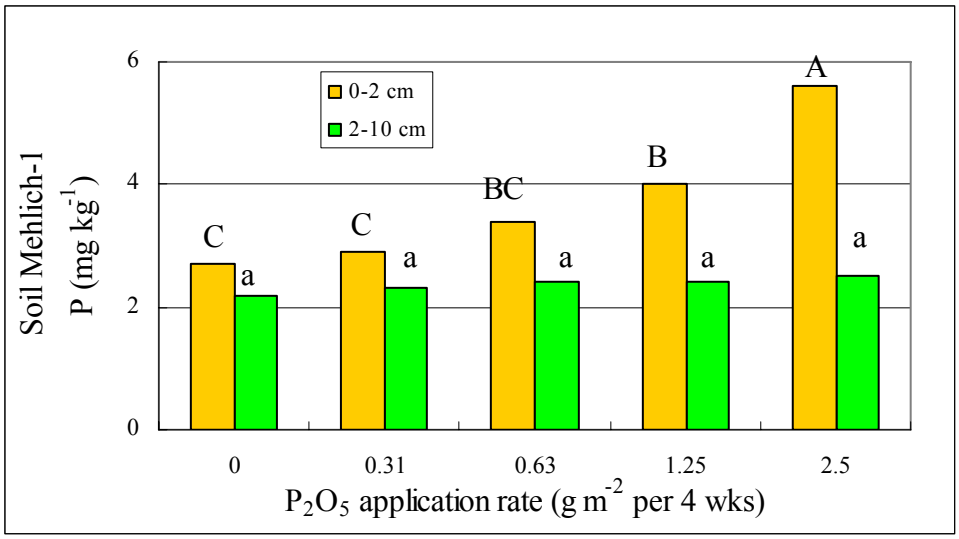

Figure 4-40. Soil Mehlich-1 P concentration as influenced by P application rate and soil sampling depth in the glasshouse soil study 3.

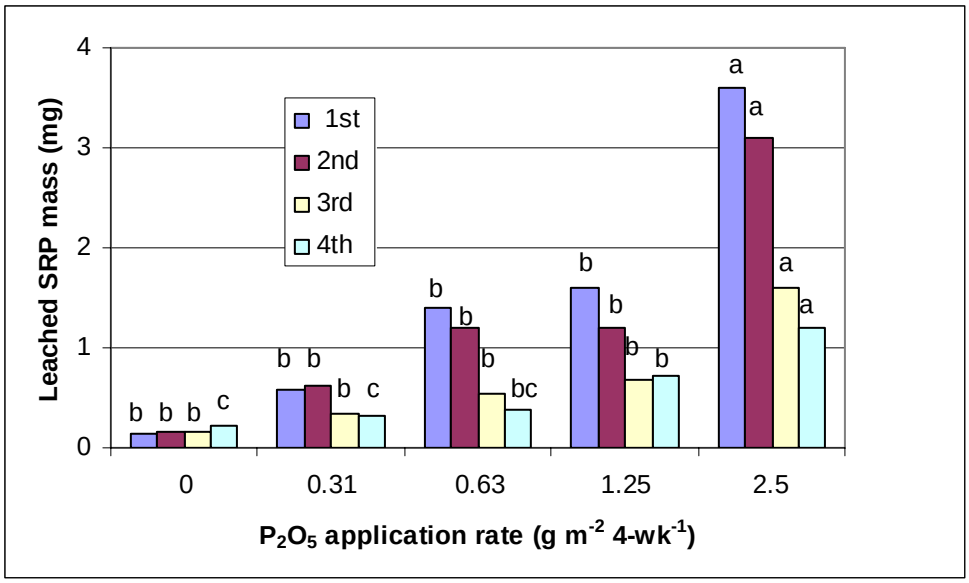

Figure 4-41. Leached SRP mass as influenced by P application rate and leaching event in the glasshouse soil study 3.

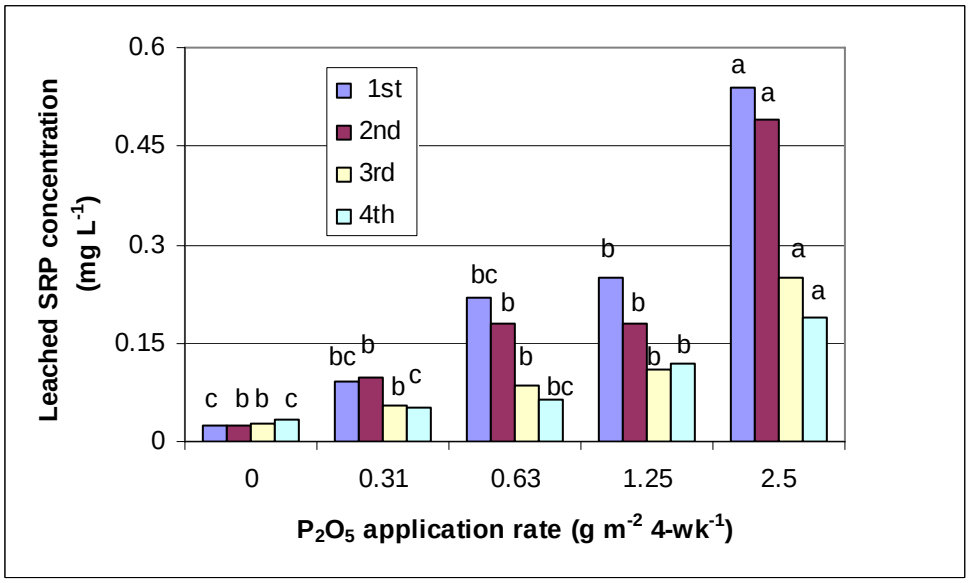

Figure 4-42. Leached SRP concentration as influenced by P application rate and leaching event in the glasshouse soil study 3.

CHAPTER 5
CONCLUSIONS

Glasshouse Hydroponic Study

The best turf quality was achieved by the highest P treatment. Turfgrass receiving P at 31 mg m^{-3} attained the highest root growth among the treatments. The critical solution P concentration for optimum shoot growth was 111 mg m^{-3}. St. Augustinegrass can be predicted to respond favorably to P applications if the tissue P concentrations are less than 1.6 g kg^{-1}. Otherwise, no additional shoot growth would be expected if all other growth factors were adequate. In practice, conventional P fertilization programs normally use soil test P status as an index which categories soil P into very low, low, medium, high, very high levels. However, the soil P value range for each category was initially designed for agronomic crops and possibly does not apply to St. Augustinegrass. Future studies may include determining a suitable soil testing procedure for St.Augustinegrass P recommendations and establishing the critical soil P level by relating it to the critical plant tissue P level.

Turf Quality in Glasshouse Soil Studies

In the glasshouse soil study 1, P application above 0.31 g m^{-2} 4-wk^{-1} on soil No.1 did not result in better turf quality in 12 out of 16 weeks. For soil No.2 (Tavares sand) and 3 (Pottsburg sand) in the glasshouse soil study 2, P application of 0.31 g m^{-2} 4-wk^{-1} achieved the best turf quality in 11 out of 12 weeks. For soil No.4 (Tavares sand) in the glasshouse soil study 3, P application of 0.31 g m^{-2} 4-wk^{-1} resulted in the best turf quality in 10 out of 12 weeks. These suggest that in terms of turf quality the minimum P application rate was somewhat above 0.31 g m^{-2} 4-wk^{-1}, which equates to an N: P_2O_5 application ratio of 16:1 assuming 5 g N m^{-2} 4-wk^{-1} was applied. This is substantially higher than common used 4:1 ratio. This finding could be used to modify the N:P:K ratio recommended for St. Augustinegrass.

Top Growth Rate in Glasshouse Soil Studies

Additional phosphate application beyond 0.31 g m^{-2} 4-wk^{-1} did not result in increased top growth for the soils tested except soil No.3 (Pottsburg sand). The top growth rate with P application of 0.31 g m^{-2} 4-wk^{-1} for soil No.3 was reduced by approximately 30% from the maximum growth rate of 2.9 g $m^{-2}day^{-1}$. A larger variation on top growth was observed and it may be due to more severe disease damage for soil No.3. Generally speaking, phosphate application of 0.31 g m^{-2} 4-wk^{-1} is the minimum rate to achieve the optimum top growth. In case of disease damage, higher rate of P application would be beneficial for recovery.

Tissue P Concentration and Critical Tissue P Concentration

Tissue P concentration varied from 1.0 to 3.6 g kg^{-1} with P application rates. For soil No.1 (Pomona sand), 2 (Tavares sand), and 3 (Pottsburg sand), turfgrass receiving no P maintained a value of 1.0 g kg^{-1}, with which turfgrass showed P deficiency symptoms, reduced turf quality, and reduced growth rate. Turfgrass receiving no P in soil No.4 maintained a value of 1.4 g kg^{-1}, which was possibly due to a higher residual labile P concentration in soil No.4. In the glasshouse soil study 1, 2, and 3, the critical minimum tissue P concentration determined was 1.8, 1.9, and 1.8 g kg^{-1}, respectively. Therefore, the critical minimum tissue P concentration for St. Augustinegrass is 1.8 g kg^{-1} to achieve the optimum growth. This differs from solution study possibly because plants biologically behave slight differently in soil from solution.

Soil P Tests and Critical Soil Test P Concentrations

Mehlich-1 P, Fe Oxide Strip P, and WEP were highly correlated to each other and they were also highly correlated to tissue P concentration and top growth rate. Among these three extractants, Mehlich-1 is the best soil P extractant for St. Augustinegrass because of higher r^2 and smaller p values. The critical WEP and Fe oxide strip P were 3 mg kg^{-1}. The critical soil

Mehlich-1 P levels were in the range from 5 to 9 mg kg^{-1} depending on soil properties. The critical soil Mehlich-1 P level tends to be lower in presence of Fe/Al oxides.

P Downward Movement and Leached P

Majority of CSP applied remained in the top 2 cm soil. Approximately 1% of P applied leached down the soil profile. Larger quantity and higher concentration of P leached in the first leaching event one week after P application. This suggests the importance of P application timing. To avoid P application before a rain event would be beneficial in preventing P leaching loss. Application of 0.31 g P_2O_5 m^{-2} 4-wk^{-1} did not result in either a larger leached P quantity or a higher concentration. This suggests that P loss through leaching can be prevented by small application rate.

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BIOGRAPHICAL SKETCH

Min Liu was born in Jingzhou, Hubei Province, China, on December 13, 1978. After receiving his bachelor's degree in soil and plant nutrition science from China Agricultural University in 2001, he came to the United States attending the University of Georgia. He received his master's degree in soil fertility with Dr. David E. Kissel working on lime requirement of acid soils. Right after that, he moved to Gainesville as a Ph.D. student with Dr. Jerry B. Sartain in 2003. He met his wife, Kehong Ma, during 2003 Christmas vacation in China and married her on April, 26, 2004. Throughout the next 3 years as a graduate student in the Soil and Water Science Department at the University of Florida, he investigated the phosphorus requirement of St. Augustinegrass. After earning his degree, Min would like to continue using his knowledge and skills in fertilizers and soil fertility at either a university or industry position.