MANAGEMENT OF PHOSPHORUS SOURCES AND WATER TREATMENT RESIDUALS (WTR) FOR ENVIRONMENTAL AND AGRONOMIC BENEFITS

By

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To my wife, ‘Bunmi, and my children, Faith, ‘Tobi, and ‘Dara.

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MANAGEMENT OF PHOSPHORUS SOURCES AND WATER TREATMENT RESIDUALS (WTR) FOR ENVIRONMENTAL AND AGRONOMIC BENEFITS

By

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Land co-application of different sources of phosphorus (P) and aluminum water treatment residuals (Al-WTR) has potential as a best management practice to reduce environmental hazard associated with excess soil P in low P-sorbing coastal plain sands. Accurate knowledge of how P-sources, source application rates, and WTR affect soil P loss and agronomic returns can enhance sound management of the wastes in watersheds for agronomic and environmental benefits. Agronomic and environmental impacts of P-sources, source application rates, and WTR were studied using four P-sources at two application rates and an Al-WTR in glasshouse, rainfall simulation and field studies. Applying P-sources at nitrogen (N) based rates will meet plant nutrient needs, while co-applying the P-sources with WTR to 0 mg kg^{-1} soil phosphorus storage capacity (SPSC) will improve P sorption properties and reduce P hazard associated with N-based rates to that observed at P-based rates. Surface applied WTR effectively reduced P concentrations of groundwater samples of P treated plots below those observed in control plots without increasing either groundwater Al concentrations or inducing plant Al phytotoxicity. Soil soluble P and P losses associated with applying moderate water soluble P-sources were minimal. Thus, environmental P hazards associated with high application rates (N-based) of P-sources can

be managed by either applying the P-sources with WTR to attain 0 mg kg^{-1} SPSC, or using a moderate water soluble P-source. The P-sources differ in P loss potentials and in relative P phytoavailability (RPP). Coefficients based on PWEP values of the P-sources are suggested to account for P loss potentials of different P-sources. Properties of P-sources, such as Total P, NaOH-P, and %solids, could affect the RPP of biosolids. Further studies will be needed to identify properties that could account for manure RPP. Sensitivity analysis of the drafted Florida P Index model indicates that all nine variables in the model are important, and all variables fell into either medium or higher impact categories. Studies are needed into all variables in the P Index and the use of continuous ratings for the variables where possible. Use of more than 3 variables to account for wide spectrum of P-sources is recommended, and coefficients based on PWEP values of the sources should be considered.

CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

Introduction

A major issue confronting agriculture in the USA is the environmental challenge of land applied phosphorus (P). The animal industry produces nearly 160 million Mg (dry matter) of manure annually, which was estimated to result in about 2 million Mg annual P excretion (Sweeten, 1992). In addition, approximately 132 billion liters of waste water is treated daily in the US, resulting in an estimated 6.3 million Mg of biosolids production yearly. The mass of biosolids produced is projected to be 7.4 million dry Mg yr^{-1} by 2010 (United States Environmental Protection Agency [USEPA], 1999). At an average P concentration of 25 kg P Mg^{-1}, biosolids represent 159,000 Mg P yr^{-1}, of which ~40% (63,500 Mg P yr^{-1}) is land applied in USA alone. The decreased availability of landfills in the USA (from ~8000 in 1988 to 3090 in 1996) suggests that land application of biosolids will increase to 48% by 2010 (USEPA, 1999; Mullins et al., 2005).

Land application of manures and biosolids residuals to meet crop nutrient needs is a major beneficial and economical method of disposal and accomplishes nutrient recycling. However, land application of the residuals based on crop N requirement (N-based rates) usually supplies P in excess of crop needs due to the lower N:P ratio in the materials than needed by the plants (Reddy et al., 1980; Pierzynski, 1994; Shober and Sims, 2003). At the N-based rates, organic sources of P can supply >5 times crop needs. Excess soil P is not harmful to plants, but offsite migration of P to surface waters is a concern, as P is the limiting nutrient for eutrophication of most freshwaters (Elliott et al., 2002a). Over 33% of US rivers, lakes, wetlands, and estuaries were reported degraded due to agricultural practices, and P losses from agricultural land have been implicated as one of the main causes of reduced water quality (USEPA, 2000; Boesch et al., 2001). Meeting the criteria for water quality without compromising the agronomic benefits of residuals land application requires proper management of the P-sources. This is especially important in the sandy soils of Florida that sorb P poorly and surround P-sensitive water bodies (Harris et al., 1996).

Phosphorus Losses and Availability to Plants

Phosphorus losses and availability to plants can vary with applied P-source, P-source rates, soil sorption properties, and management practices. The solubility, bioavailability and transport potential of P varies among biosolids, manures and fertilizer types (Brandt et al., 2004; Leytem et al., 2004; Elliott et al., 2005). Wide variability in total P (TP) concentrations has been reported in biosolids (Keeney and Walsh, 1975; Dowdy et al., 1976; Sommers, 1977) and manures (Sommers and Sutton, 1980). Over 70% of the TP in residuals occurs in inorganic P forms (Gerritse and Vriesema, 1984; Sharpley and Moyer, 2000; Dentel et al., 2002). Organic forms, if present in significant amount in fresh manures, rapidly mineralize to inorganic forms on storage (Peperzak et al., 1959; Gerritse, 1981; Crouse et al., 2002). Inorganic P forms are also readily available for uptake by algae and aquatic plants and represent immediate risks to the water quality. This explains why studies on organic sources of P often focus on the reactions of inorganic P forms with soil components.

Nutrient management to reduce P losses from residuals amended fields necessitates understanding and accounting for differences in the phytoavailability of P in various P-sources. Accurate estimates of P phytoavailability may help tailor manure and biosolids applications to plant needs and thereby minimize the buildup of bioavailable P, which can degrade sensitive aquatic systems. Neutral ammonium citrate extraction (Association of Official Analytical

Chemists (AOAC), 1995) is used to determine the guaranteed plant available P in commercial mineral fertilizer. However, Elliott et al. (2005), showed that the extractant failed to quantify biosolids P phytoavailability. A recent study by Zvomuya et al. (2006) suggests that the P availability of soil-applied composted and non-composted manures can be predicted from the water extractable P and the total P concentrations. Phosphorus availability from manure and composts has been assessed using crop uptake in pot, laboratory incubation, and field experiments (Eghball et al., 2002; Eghball et al., 2005). A 50% effectiveness of biosolids-P relative to fertilizer-P was suggested in the USEPA process design manual (USEPA 1995), while 40% was recommended in Ontario, Canada regulations (Ontario Ministries of the Environment and Energy (OMEE), 1996). However, research indicates P phytoavailability can vary from ~0% to 100% of fertilizer P (de Haan 1981; Smith et al., 2002; O'Connor et al., 2004). Biosolids-P phytoavailabilty depends on the waste water treatment process used, which dictates the forms and solubility of P in the sources. O'Connor et al. (2004) classified biosolids-P into three phytoavailability categories: high (>75% as available as fertilizer-P), moderate (25% to 75%), and low (<25%), based on a 4-month greenhouse study. The data need to be validated for longer periods, and preferably, in the field. A longer study period (at least 1 year) is necessary because the P that is not bioavailable in the short term may ultimately be released by various biochemical processes.

Understanding the contribution of P-sources to P loss potentials is also critical to mitigate P loss from agriculture to the environment. Coefficients suggested to access P loss potentials of different P-sources include the Phosphorus Saturation Index (PSI) (Elliott et al., 2002b), water extractable P (WEP) (Brandt et al., 2004; Wolf et al., 2005), Phosphorus Source Coefficient (PSC) (Leytem et al., 2004; Elliott et al., 2006), and varying measures of soil test P. The PSI was developed as an index of P-sources solubility and relates well with the P losses from varying biosolids P-sources (Elliott et al., 2002b), especially for biosolids whose P solubility is controlled by Fe and Al. The index is calculated as ratio of ammonium oxalate extractable P (P_{ox}) to the sum of oxalate extractable Fe and Al (Fe_{ox}, Al_{ox}):

$$PSI = ([P_{ox}] / [Al_{ox}+Fe_{ox}])$$

(concentrations in mmol kg^{-1} biosolids)

Conceptually, PSI is the molar ratio of total sorbable P to the sum of Al and Fe components capable of P fixation. A PSI value < 1 indicates excess P sorption sites in materials and minimal labile P available for leaching, whereas PSI value > 1 indicates greater biosolids-P than the P sorption capacity of the materials. Elliott et al. (2002b) found that biosolids with PSI ≤ ~1.1 exhibited no appreciable P leaching, whereas a biosolids cake (PSI = 1.4) and its pelletized form (PSI = 1.3) exhibited significant leaching losses. The biosolids PSI appears useful for identifying biosolids with potential to enrich leachate P when applied to low P-sorbing soils. However, soil with even a modest P-sorption capacity may mask the differences in biosolids-P leachability. Also, the PSI is less useful to account for the P leachability in the whole spectrum of the organic sources of P, especially materials rich in Ca, and Mg where P solubility is controlled by the Ca and Mg (e.g., manures). The physical state of the materials such as % solids and particle size can also affect the source P solubility and the potential for P loss or availability to plants. O'Connor and Sarkar (1999) indicated that pelletization of biosolids by heat drying resists degradation and reduced P release, and agree with Smith et al. (2002) that P availability is reduced by thermal drying of biosolids. Thus, there is a need for an index (or indices) of the P-sources that integrates both physical and chemical properties to account for P lability.

The importance of P-source lability to soil P loss is well appreciated by some of the P indices being developed by most States in US, including Florida. The P-source coefficients and other variables in the P Index were assigned based on professional judgments of the scientists developing the model, and need to be validated. While some states (e.g., Pennsylvania) have validated the P-source coefficients used in the P Index with experimental data, most P Indices including the Florida P Index, are yet to be validated. Determining the sensitivity of the draft Florida P Index to the P-source coefficients and other variables in the model will also be a necessary step towards validation of the model. Sensitivity analysis not only indicates the impact of each variable (including P-source) on the P Index score, but can assist in identifying areas of priority in future research on P loss potential as estimated by the P Index. Improving the Florida P Index will ensure more accurate assessment of vulnerability of Florida landscapes to P loss and enhance management to reduce P losses to the environment.

Phosphorus Application Rates and P Losses

Accumulation of P in surface soils beyond levels needed for optimal crop yields often results when organic sources of P are applied at N-based rates (Reddy et al., 1980; Pierzynski, 1994; Peterson et al., 1994; Maguire et al., 2000). Soil P loads in excess of those needed for optimum crop production increase the potential for nonpoint P loss through runoff and leaching. Rechcigl et al. (1992) showed a strong correlation between P fertilizer surface-applied to bahiagrass (*Paspalum notatum* Flugge) pastures and dissolved reactive P (DRP) in surface runoff. Thus, fertilizer-P was identified as a major contributor to a 310 km^2 algae bloom in Lake Okeechobee, FL in 1986. Runoff P concentrations decreased 33 to 66%, and total P losses in runoff decreased 17 to 78%, by reducing fertilizer-P application rates. Biosolids applied at N-based rates to corn (Zea mays) added from 93 to 294 kg P ha^{-1} of which only ~25 kg P ha^{-1} was removed by the plants (Stehouwer et al., 2000). Studies in the past 30 years consistently implicate N-based rates with soil P build up and P loss to the environment (Kelling et al., 1977; Reddy et al., 1980; Kick, 1981; Pierzynski, 1994; Peterson et al., 1994; Maguire et al., 2000). As P-sources differ in solubility, the environmental hazard of all P-sources is not expected to be the same. For example, P-sources of lower solubility might be applied at N-based rates without excessive P losses to the environment. This hypothesis, however, needs to be tested using suitable procedures such as rainfall simulations or field studies.

Agronomic and Environmental Soil P Thresholds

Several researchers have attempted to identify the critical soil test P (STP) levels above which P delivery to water bodies is unacceptable. These environmental STP thresholds are commonly based on readily available, agronomic soil P testing procedures. The environmental thresholds can be established based on the rationale that soil P in excess of crop requirements is susceptible to release in runoff and drainage waters. However, equating agronomic and environmental thresholds can be inadequate as the processes by which crops access soil P are different from those that determine the susceptibility of source-P to solubilization by subsurface leaching or surface runoff (Kleinman et al., 2000). Plants can solubilize soil water-insoluble P compounds and enhance P uptake by the production of organic acids in root exudates. Thus, estimates of adverse water quality effects of the soil P levels need not be directly inferable from the crop response (Sharpley et al., 2003). A developing consensus among researchers is that it is possible to maintain STP at levels that optimize crop yields, while minimizing the risk of offsite P transport (Higgs et al., 2000).

Studies show that dissolved runoff P (DRP) is linearly related with STP in the topsoil (Pote et al., 1999; McDowell and Sharpley, 2001; Andraski and Bundy, 2003). When a sufficiently wide range of STP levels considered, however, the relationship becomes curvilinear (Fig. 1-1) due to saturation of P sorption sites on the soil (McDowell and Sharpley, 2001; Elliott et al., 2004). The curvilinear relationship between DRP and STP can be described by exponential models, or by a simple split-line model that defines two linear sections, with a change in slope occurring at the so-called "change point" (Elliott et al., 2004). The change point identifies the STP beyond which environmentally significant amounts of added P are expected to be mobilized by rainwater because soil P-sorbing sites have become sufficiently filled. Below the change point, much of the added P is retained by the soil (Fig. 1-1).

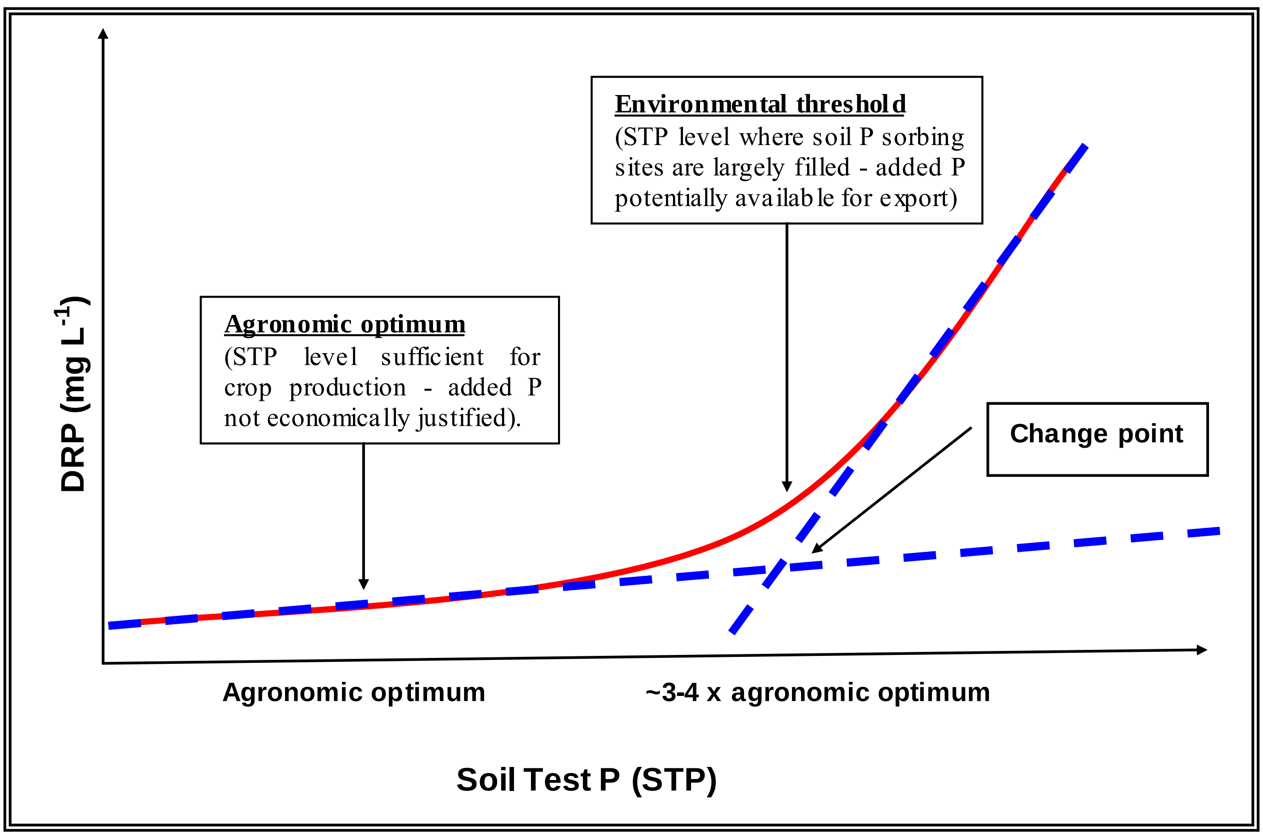


Figure 1-1. Illustration of agronomic and environmental threshold concepts (Elliott et al., 2004).

The change point is typically ~3-4 times the agronomic threshold. In Pennsylvania, no additional P is recommended for crop fertilization beyond STP levels of 50 mg kg^{-1} P (Mehlich-

3), considered sufficient for crop production (Agronomy Guide, 2002). The environmental threshold, however, is considered to be 200 mg kg^{-1} STP (Sharpley et al., 2001). The state of Maryland defined 75 mg kg^{-1} Mehlich-1 P, which is three times the agronomic critical level, as the environmental STP threshold (Coale et al., 2002). Texas uses 200-500 mg kg^{-1} Bray-1 P (depending on site and watershed characteristics) as environmental soil test thresholds, beyond which no further P applications are allowed until changes that could lower the site's P loss potential. In Florida, Mehlich-1 P values above 30 mg kg^{-1} are considered high from an agronomic standpoint, and a value above 60 mg kg^{-1} is considered very high (Kidder et al., 2002). Elliott et al. (2004) postulated that, on average, the environmental threshold is between three to four times the agronomic optimum. Thus, reducing the soil test P by 75% with amendment (e.g., WTR) can minimize environmental hazard and optimize the agronomic benefits.

Various chemical extractions (Mehlich I and III, Olsen, Bray, water or 0.01 M $CaCl_2$, anion exchange resin, Fe-oxide strip, etc) are suggested as environmental soil tests for estimating labile P (Gartley and Sims, 1994; Simard et al., 1995). The relationship between extractable soil P concentration and dissolved P concentration in runoff water is not unique and varies with soil type (Sharpley, 1995) and the P-source. Thus, in risk assessment of P desorption for a range of soils, parameters related to an intensity factor (solution P concentration) and capacity factor (P sorption capacity) should be considered (Beauchemin and Simard, 1999). The degree of P saturation (DPS) of soil surface is a promising variable to predict this risk (Sharpley, 1995; Beauchemin et al., 1996; Pote et al., 1996; Provin, 1996; Nair et al., 2004).

The concept of DPS integrates both intensity and capacity factors, as it measures the intensity of P accumulation while describing the potential of P to desorb from soil matrix into soil solution (Sharpley, 1995). Various ways of estimating this parameter could be good indicators of a soil's potential to release environmentally significant amounts of P. Relationships between water-soluble P (deionized water) and degree of P saturation estimated from oxalate extracts (DPS_{ox}) gave a change point at 20% DPS_{ox} for manure impacted surface and subsurface Florida sands (Nair et al., 2004).

The degree of P saturation calculated from 0.2M oxalate extractable P, Fe, and Al (DPS_{ox}) is also closely related to P concentrations in leachate waters (Leinweber et al., 1999; Maguire and Sims, 2002), suggesting that DPS_{ox} can be a suitable tool for predicting subsurface P losses. Soils with DPS_{ox} of >25% contributed to ground water pollution by P in the Netherlands (Breeuwsma et al., 1995). The 25% value corresponds to 0.15 mg total P L^{-} in ground water in the Netherlands. Values for DPS_{ox} of >30% in topsoils have been identified as a threat to water quality degradation in Mid-Atlantic U.S. soils (Paulter and Sims, 2000), and associated with increased P losses in runoff (Pote et al., 1996).

The University of Delaware rates soils with Mehlich-1 P values >50 mg P kg^{-1} as excessive (Paulter and Sims, 2000). Relationship between M-1P values and DPS_{ox}, indicated M-1P concentration of 30 mg P kg^{-1} corresponds to a DPS_{ox} value of 22%, whereas a 60 mg P kg^{-1} value corresponds to a DPS_{ox} value of 28% (Nair et al., 2004). The study by Nair et al. (2004) suggest that DPS_{ox} value of 25% corresponds to 50 mg P kg^{-1} identified by Paulter and Sims (2000) to be excessive. The differences in the threshold DPS values determined could result from using different α-values in the calculation of the DPS. Paulter and Sims (2000) used an alpha value of 0.68 to calculate DPS, whereas Nair et al. (2004) used a value of 0.50. The alpha value for Spodosols of the Lake Okeechobee basin in Florida is 0.55 (Nair and Graetz, 2002), which is close to the 0.5 values used by Nair et al. (2004). Nair et al. (2004) also observed a change point at DPS_{ox} values of 16-24% (95% confidence interval) in Florida soils.

Another index that could identify environmental thresholds is the soil P storage capacity (SPSC) values suggested by Nair and Harris (2004). The SPSC concept is an improvement on the DPS as it quantitatively indicates the P storage capacity of a soil (how much P could be safely added to a soil volume). While the environmental threshold of the SPSC term is known to be at phosphorus saturation ratio (PSR) value of 0.15 (Breeuwsma and Silva, 1992; Nair and Harris, 2004), the agronomic threshold has not been considered. The agronomic threshold is expected to be below the environmental threshold and, hence, should be environmental friendly as a basis for P-sources land application. Phosphorus rates based on agronomic thresholds will be economically justified, as it will ensure applying the P-sources to meet plant needs and will keep the soil solution below the environmental threshold.

Water Treatment Residuals (WTR) as Soil Amendments

Numerous studies have been conducted in Florida over the years utilizing a wide variety of amendments, amendment rates, soils, P-sources, and P loss mechanisms to identify best managements practices to reduce negative environment P impacts on the aquatic systems (e.g., Allen, 1988; Anderson et al., 1995; Alcordo, et al., 2001; Matichenkov et al., 2001). There is increasing interest in using soil amendments to counter excess soil P and, hence, reduce dissolved P in runoff and leachate from manure- and biosolids-amended soils.

Recent work by O’Connor and colleagues (O’Connor and Elliott, 2001; O’Connor et al., 2002a) has shown water treatment residual (WTRs) to be effective soil amendments to immobilize and manage the excess soil P in Florida soils. The residuals, WTRs, are Al and or Fe rich waste products of municipal water treatment. The aluminum and iron salts added during water treatment hydrolyze to form amorphous metal oxides that sorb organic matter, color, turbidity, phosphorus (P) and other wastewater constituents. Commonly, WTRs are land-filled; however, as landfill space becomes less available and more costly, land application is considered as a method of beneficial recycling WTRs that can also address P related water quality concerns.

Studies by Moore and colleagues (Moore and Miller, 1994; Shreve et al., 1995; Moore et al., 2000) document effective control of P solubility by Al added to poultry manure. O'Connor and Elliott (2001) also co-applied Al- water treatment residual (Al-WTR) with several biosolids, fertilizer, and two manures. They demonstrated almost complete control of P leaching through amended Florida sands initially low in P, regardless of P-source because soluble P levels were dramatically reduced in the soil/amendment mixtures. Laboratory studies (O'Connor et al., 2002a) also showed that Al-WTRs adsorb large amounts of P, and that poorly P-sorbing Florida soils could adsorb significantly more P following amendment with modest amounts of Al-WTRs. The soil P retained by Al-WTR is irreversibly bound, barring unrealistic changes in environmental conditions ($pH < 4$) that dissolve the WTR solid. Iron-based WTRs, or salts, can also effectively sorb P, but are subject to P release under reducing condition (Ann et al., 2000).

Aside from P solubility control, other potential benefits of land applied WTR are: increased plant available nutrients (e.g., nitrogen and total organic C) (Lin, 1988; Dempsey et al., 1989; Elliott et al., 1990; Elliott and Dempsey, 1991), and increased aggregate stability, water retention, aeration, and drainage capacity (El-Swaify and Emerson, 1975; Rengasamy et al., 1980; Bugbee and Frink, 1985). The amorphous hydrous oxides in WTR may also increase cation exchange capacity of coarse-textured soils (American Society of Civil Engineers et al., 1996), while alkaline stabilized WTR e.g., stabilized with $CaCO_3$) can in addition serve as a liming agent. Such enormous benefits of land applied WTR and other similar BMP may need to be compensated for in P management tools such as Florida P Index. However, potential negative impact of the residuals (WTR) needs to be evaluated before making a case for such compensation.

Potential negative impacts of Al-WTR land application could include excessive immobilization of plant-available soil P and Al toxicity. Heil and Barbarick (1989) noted severe P-deficiency symptoms associated with 25 g WTR kg^{-1} soil planted to sorghum-sudangrass [*Sorghum bicolor* (L.) *Moench Sorghum X drummondii (Steudel) Millsp*. Chase]. A decreased P concentration in blue grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.) was found by Ippolito et al. (1999) when the rate of WTR was increased. Rengasamy et al. (1980) reported reduced P uptake in maize (*Zea mays* L.) with WTR addition, while Elliott and Singer (1988) and Bugbee and Frink (1985) found reduced P concentrations in tomato (*Lycopersicon esculentum* L.) and lettuce (*Lactuca sativa* L.) grown in WTR-amended potting media. However, in a study by Naylor and Carr (1997), an Al-WTR (116 g Al kg^{-1}) amendment reduced exchangeable P level in the soils, but did not limit plant growth. Brown and Sartain (2000) also reported reduction in leaching P from a USDA green soil profile amended with 25 g kg^{-1} by weight with Fe-based WTR while maintaining adequate plant P uptake. The data suggest that WTRs can reduce P solubility in high P soils without inducing a P deficiency. Adding air-dried Al-WTR to soils at rates of 2 and 20 g kg^{-1} improved aggregation, but the high application rate decreased germination and decreased P uptake by maize, *zea mays* (Rengasamy et al., 1980). Yields of fescue grass (*festuca ovina 'glauca'*) grown in the greenhouse decreased with increasing Al-WTR application rates (0, 10, 20, and 40 g kg^{-1}) to soil and the trend contributed to reductions in plant-available P that were corrected with supplemental P fertilizer (Lucas et al., 1994). The possibility of reducing crop yield as a result of P deficiency following application of WTR calls for in-depth study into the application rate of the amendment that will be environmentally and agronomically beneficial.

A better understanding of the change in chemistry of the soil as a result of WTR application and impacts on the plants is needed as the WTRs can affect soil reaction (pH), solubility of P, adsorption of P and speciation and distribution of other chemicals (notably Al). Soluble aluminum has been implicated as the most common source of phytotoxicity in acid soils (Arkin and Taylor, 1981), and a common yield-limiting factor in acid soils. Aluminum is a phytotoxic element when present at excess concentrations in solution. Cornell Recommends (1992) suggest that Morgan soil test aluminum values in the range of about 1 to 50 mg kg^{-1} are normal, with higher values being excessive, but not necessarily phytotoxic. Many soils exceed 50 mg kg^{-1} soil test aluminum and continue to remain productive. Aluminum concentrations can be sufficiently high in acid soils with pH values of <5.5 to be toxic to plants (Brady and Weil, 2002). The aluminum species (Al^{3+}) responsible for the phytotoxic effect is often a small fraction of the total aluminum in the soil solution. Alum-treated litter or alum hydrosolids (similar to WTR) have neutral or alkaline pH, and Al exist as insoluble Al oxides, which should not release toxic Al or produce acidity in soil or aqueous systems (Peters and Basta, 1996). However, plants have mechanism (including releasing of exudates) to assess soil nutrients and the impact of the applied Al-rich WTR on plants should be evaluated, especially in Florida soils with pH < 5.5.

Changes in basic soil properties that affect nutrient availability to plants as a result of WTR application demand a better understanding of the chemistry and suitability of soil test methods for the available P that correlate well with plant uptake. Inadequacy of STP as an estimate of plant response could lead to incorrect P management for agronomic benefits. Reports of plant response as a function of soil test P methods applied to WTRs or WTR-amended soils yield conflicting results. Basta et al. (2000) evaluated three Al-WTRs as soil substitutes and the ability of soil tests to predict P adequacy for bermudagrass (c*ynodon)*. Soil tests indicated P deficiency for two of the WTRs and a control soil, and P concentrations in tissue grown on the unfertilized WTRs and soil were below adequate levels. Fertilization (50, 100 and 200 mg P kg^{-1}) increased Bermuda grass yield and tissue P concentrations for the soil, but not for the WTRs. Water-soluble P and Olsen P were useful in predicting the ability of WTRs to support growth, but not P adequacy, while Mehlich-3 P (M3P) soil test overestimated plant available P in WTRs due to the dissolution of P adsorbed by amorphous Al. Water extracts were judged adequate to predict P adequacy in WTR-amended soil (Basta et al., 2000). However, these findings need to be investigated using additional soils and different P-sources.

Cox et al. (1997) conducted a greenhouse study to determine Al-WTR effects on inorganic forms of P and availability to wheat (*Triticum aestivum* L.) in a thermic Aquic Hapludult. Of the inorganic P fractions studied, loosely-bound (1 M NH_4Cl-extractable) P was the best predictor of P availability in Al-WTR amended soil, but Mehlich-1 P (M-1P) was also a good indicator. However the suitability of M-1P may need to be studied especially in Florida sands. Another method to assess plant available P in WTR amended soils is the iron oxide filter paper method, sometimes referred to as ″strip P" or the "Pi soil test″ (Sharpley, 1991; Sharpley, 1993 a, b; Chardon et al., 1996; Pote et al., 1996; Menon et al., 1997). The principle involves an Fe-oxide strip acting as an "infinite sink" for the P that can be desorbed from a soil and, thus, measures the potential of a soil to continue to release P to plants. Pote et al. (1996) found the method accurately predicted the quantity of P susceptible to runoff, and was better than most agronomic soil P tests. Sharpley (1993a) also reported that Fe-oxide "strip P" was a good indicator of the biological availability of P in runoff waters to algae.

O'Connor et al. (2002b) utilized a greenhouse study to determine the bioavailability of biosolids- and manure-P as compared with fertilizer-P. Water extractable P and iron strip P were identified as potential P test methods for labile P in biosolids and WTR amended soils where Mehlich 1 test failed. The suitability of various soil tests is expected to vary with soil, soil reactions, P-sources, and P forms and could be more complex in WTR treated soils. Fertilizer P requirements can differ in WTR-amended and unamendeds soils, so careful selection of soil testing methods is necessary.

Hypotheses and Research Objectives

A good understanding of agronomic and environmental impacts of P-sources, P or source application rates and P sorbing amendments such as WTR is necessary to derive best management practices (BMP) for P-sensitive areas in Florida. Conflicting reports of the impact of the different amendments on the plant nutrient uptake and yield could be resolved through the use of an appropriate soil test methods, especially when WTR is applied. Also, the environmental benefits of WTR application could be optimized, without compromising the agronomic importance, if applied at a rate to target only the P in excess of plant needs. Thus it was hypothesized that:

I. P-based rates of different organic sources of P, without WTR, optimize P uptake.

II. N-based rates of different organic sources of P, with WTR, optimize P uptake.

III. Indices exist to account for P phytoavailability of different P-sources

IV. Suitable soil test methods exist to access P bioavailability in Florida sands receiving organic sources of P and WTRs.

V. Amendment rates selected in (I and II) that optimize P uptake also minimize P leaching and runoff.

VI. Indices exist to account for P loss potentials of different P-sources

In summary the objectives of this study were to evaluate the environmental and agronomic impacts of different P sources and WTR and to determine the rate of P-sources and WTR that optimize environmental and agronomic benefits. The specific objectives of the studies are:

I. Determine the rates of WTR and organic sources of P that optimize plant P uptake while minimizing environmental P hazards.

II. Evaluate the impact of selected amendments (WTR and organic sources of P) rates on leaching and runoff P.

III. Validate the expected impacts of selected amendments (WTR and organic sources of P) rates on P uptake and P loss in field settings.

IV. Identify suitable soil test methods for P bioavailability in soils amended with different P-sources and WTR.

V. Evaluate the sensitivity of the draft Florida P Index model to P-source coefficients and other variables in the model.

Study Approach

Three (3) major experiments were carried out to test the hypotheses:

- a glasshouse study
- a rainfall simulation study and
- a field study

The main objective of the glasshouse study was to study the agronomic impacts of P-sources and WTR treatments. The rainfall simulation experiment was designed to evaluate the impacts of organic sources of P, P-source application rates, and WTR on leached and runoff P.

The field experiment was used to validate the results of the glasshouse and rainfall simulation experiments.

The three studies used the same four P-sources, which are Boca Raton biosolids, Pompano biosolids, poultry manure, and Triple Super Phosphate (TSP). The sources were chosen to represent varying types of P-sources (manure, biosolids, and mineral source) and to include high water soluble P biosolids (Boca Raton biosolids), and medium water soluble P biosolids (Pompano biosolids). The materials were applied at low and high rates (P-based and N-based rates in the glasshouse and field study). Two levels of WTR (0 and 20 Mg WTR ha^{-1}, 0 and 1% oven dry basis, respectively) were surface-applied in the field and rainfall simulation studies. In addition to the 0 and 20 Mg WTR ha^{-1}, a 50 Mg WTR ha^{-1} (or 2.5%) rate was used in the glasshouse study, and the materials were soil-incorporated.

Both field and glasshouse studies used bahiagrass as the test plant, while ryegrass was planted during the cool season in the glasshouse study. The rainfall simulation study did not include plants, as the National Phosphorus Research Protocol (National Phosphorus Research Project, 2001) was adopted. Details of the studies are included in the subsequent chapters.

Dissertation Format

This dissertation is written as reports from the three major studies to address specific objectives of the study and in manuscript format intended for journal publications. Chapter 2 reports on the characteristics of the amendments and soils used in the three studies. Chapters 3 and 4 evaluate the agronomic impacts of the treatments in the glasshouse and field settings, respectively and thus tested hypothesis I, II and III. An attempt to identify suitable soil test methods for WTR-treated Florida sands and test hypothesis IV was made using data from the glasshouse and the field study, and is reported in Chapter 5. The basis for application rates of the

WTR to ensure optimum agronomic benefits is discussed in Chapter 6. Chapter 7 reports on impacts of P-sources, WTR, and P rates on P losses (environmental impacts) in a rainfall simulation study and hence tested hypothesis V. Chapter 8 is the report on evaluation of coefficients that could account for P loss potential of different P-sources when land applied as tested by hypothesis VI. The impact of WTR on P losses was validated using ground water samples collected from the field study and are reported in Chapter 9. The Florida P Index is expected to assist in P-source management in Florida soils. Thus, a sensitivity analysis of the drafted Florida P Index is reported in Chapter 10. Overall summary and conclusions are presented in Chapter 11.

CHAPTER 2
CHARACTERIZATION OF AMENDMENTS AND SOILS USED IN THE STUDY

Introduction

Compositions of organic sources of P could be important from both environmental and agronomic perspectives, as they are expected to affect P availability to plants or P release to water via runoff and leaching. The chemical compositions (forms and amount of P and other elements) of the amendments used could assist in understanding P reaction chemistry and availability after addition to soils. Organic sources of P usually contain lower Total P, and soluble P concentrations, and a wider variety of chemical elements, than mineral P-sources. The variation in elemental compositions of biosolids depends on the treatment processes and the quality of the influent wastewater (O'Connor et al., 2004). Manure composition also depends on the source (Sommers and Sutton, 1980; Sims and Wolf, 1994; Duo et al., 2001), but is less variable than biosolids.

The soils being amended with P-sources can also determine the extent of P losses. Florida soils are dominated by Spodosols, which occur along the hydrologic continuum from the uplands to aquatic systems. Most Spodosols are sandy, with water tables fluctuating between the spodic subsurface horizon and the surface A-E horizon (Soil Survey Staff, 1996). Low P-sorbing, sandy surface soils with high water tables tend to promote rapid surface and subsurface flows, which enhance P transport (Allen, 1988). Substantial accumulation of P often occurs in the Al-rich spodic horizons, which can serve as sources or sinks for P, depending on its degree of P saturation. Phosphorus, especially when organic sources are added at N-based rates, can easily accumulate in, and exceed the sorption capacity of the surface soil and promote P transport to adjacent water bodies.

This chapter describes the chemical and physical characterization of the P-sources, WTR, and soils used in studies reported in subsequent chapters.

Materials and Methods

Amendments and Soil Selection

Phosphorus sources used for the glasshouse, field and rainfall simulation studies were:

- Boca Raton biosolids
- Pompano biosolids
- Poultry manure
- Triple Super Phosphate (TSP)

The sources chosen represent varying types of P-sources (manure, biosolids, and mineral fertilizer), and materials with different water soluble P concentrations. The two biosolids (high water soluble-P, Boca Raton biosolids, and moderate water soluble-P, Pompano biosolids) represent biosolids that could supply excessive P when land-applied. All P-sources were obtained from Florida. The two biosolids, Pompano and Boca Raton, were obtained from the cities of Pompano Beach and Boca Raton, FL, respectively. Poultry manure was obtained from Tampa Farms in Indiantown, FL., a large egg-laying operation. Triple super phosphate (TSP) is a typical P mineral fertilizer applied to Florida crops. The WTR was obtained from a domestic water treatment plant in Bradenton, Fl.

The site for the field study, Kirton Ranch, is a cattle pasture located on the eastern border of Okeechobee County, eleven kilometers northeast of Okeechobee, north of the Lake Okeechobee. The soil is Immokalee fine sand, a typical Florida Spodosol. The Immokalee soil is classified in the Arenic Alaquods taxonomic group, and has distinct A, E and B_h horizons. Initial samples to characterize the soil were taken from the first 5 cm of the A horizon, the middle of the E horizon (~ 20-30 cm from the soil surface); and the Bh horizon (75-90cm) before amendment application. The top soil (0-15cm) of another sample of the Immokalee fine sand was used for the glasshouse experiments and the rainfall simulation experiments. Bulk samples were collected from the Southwest Florida Research and Education Center (SWFREC), which is 3 km north of Immokalee, Florida.

Amendments and Soil Analysis

The soil samples from the field and the bulk soil taken for the glasshouse and the rainfall simulation studies were air-dried, thoroughly mixed, and sieved (<2mm) before analysis. Both the soils and the amendments were analyzed for Total P, Fe, Al, Ca, Mg by inductively coupled argon plasma (ICAP) spectrometry, following digestion according to EPA Method 3050A (USEPA, 1986). Oxalate-extractable P, Fe, Al, Ca, and Mg were determined by ICAP after extraction with solutions of 0.1 M oxalic acid plus 0.175 M ammonium oxalate (pH = 3.0) at a 1: 60 solid:solution ratio, following the procedures of Schoumans (2000). The suspensions were equilibrated for 4 h in the dark with continuous shaking, centrifuged, filtered through a 0.45-µm filter, and analyzed for P, Fe, Al, Ca, and Mg by ICAP within 24 h after extraction.

The Degree of P saturation (DPS_{ox}) values of the soils were calculated from oxalate extractable P Fe, and Al as:

$$DPS_{ox} = [(P_{ox})/\alpha(Al_{ox} + Fe_{ox})]$$

where P_{ox}, $Al_{ox,}$ and Fe_{ox} are oxalate extractable P, Al, and Fe concentrations in mmoles and $\alpha = 0.55$ (Nair et al., 2004).

The soil P storage capacity (SPSC) values were also determined from the P_{ox}, Al_{ox}, and Fe_{ox} values of the soils as:

SPSC (mg kg^{-1}) = $[(0.15\text{-PSR})*(Al_{ox} + Fe_{ox})]*31$
Where PSR = Phosphorus saturation ratio = $[(P_{ox})/(Al_{ox} + Fe_{ox})]$

Biosolids PSI values were calculated using the same formula as for soil PSR values, but utilized P_{ox}, Al_{ox}, and Fe_{ox} of the biosolids. The amendment P storage capacity (APSC) values of the P-sources and the WTR (corresponding to SPSC) were calculated as:

APSC (mg kg^{-1}) = $[(0.15\text{-PSI})*(Al_{ox} + Fe_{ox})]*31$
Where PSI = Phosphorus sorption index = $[(P_{ox})/(Al_{ox} + Fe_{ox})]$

Total C and N of the amendments were determined by combustion at 1010 °C using a Carlo Erba NA-1500 CNS analyzer. Total C was determined on representative soil samples. Soil reaction (pH) was determined on fresh materials (1:2 solid or soil:solution ratio). Percent solids were determined by drying materials at 105 °C (American Public Health Association, American Water Works Association, and Water Environmental Federation (APHA/AWWA/WEF), 1995) to constant weight.

Soils and amendments were analyzed for electrical conductivity (EC), Mehlich-1 P, Water extractable-P (WEP) and Iron strip-P (ISP). Water-extractable P was determined by extracting each soil sample with water at a 1:10 soil to water ratio (1:200 ratio for amendments) for 1 h, and determining P on the filtrate collected after passing through a 0.45-µm filter (Self-Davis et al., 2000). Iron strip-P determination involved extracting solids in a centrifuge tube containing a strip of filter paper coated with Fe-oxide (a strong adsorbent for P) in 0.01M $CaCl_2$ (Chardon et al., 1996). The suspension was shaken with the Fe-strip paper for 16 h, and the P sorbed by the Fe-oxide on the filter paper was extracted by 0.1M H_2SO_4. Mehlich 1-P was determined by shaking the samples with 0.0125 M H_2SO_4 in 0.05 M HCl solution at a ratio of 1:4 soil:solution ratio for 5 minutes (Hanlon et al., 1997). Extracts were immediately filtered through Whatman Nº 42 filter paper and analyzed colorimetrically by the Murphy and Riley method (1962). Water-soluble-P and Iron strip-P concentrations were determined colorimetrically in each of the extracts with the Murphy and Riley (1962) procedure.

Fractionation of the forms of P in the sources involved sequential extraction of the samples with KCl, NaOH, and HCl solutions, in that order (modified from Chang et al., 1983). The sequential extraction started by shaking the materials with 30 mL KCl solution for 2 h, after which the solution was centrifuged, filtered (0.45 µm), and analyzed for soluble reactive P (SRP) by Murphy and Riley (1962) colorimetric procedure. The residuals from the first extraction step were then extracted with 30 mL of 0.1M NaOH overnight for 17 h, filtered, and SRP measured in the extract. The last step of the extraction involved shaking the residuals from step 2 with 0.5M HCl for 24 h and analyzing the extract for SRP. The KCl fraction, considered exchangeable P, represents the readily available P forms to plants. The NaOH –extractable P represents the Fe- and Al-bound P fraction that can buffer the soluble P forms, while the HCl extractable P is the Ca and Mg-bound P that can be important in soil reaction of manure and some biosolids amended soils. The sum of the three fractions (KCl-, NaOH-, and HCl-extractable P), is usually defined as inorganic P (Sui et al., 1999; O'Connor et al., 2004), though NaOH can extract some organic P.

Standard QA/QC protocols were observed during the sample collection, handling and chemical analysis. For each set of samples during chemical analysis, a standard curve was constructed ($r^2 > 0.998$). Method reagent blanks were appropriately used, as well as certified standards. A 5% matrix spike of the set was used to determine the accuracy of the data obtained (recovery ranging from 96-103%), and another 5% of the set to determine the precision of the measurements (duplicates). Analyses that did not satisfy the QA/QC protocol were rerun.

Results and Discussion

Amendments (P-sources and WTR) Characterization

All organic sources of P had pH values of ~7.6 (Table 2-1), whereas TSP was slightly acidic (pH of 5.9); all pH values fell within the typical pH range for soils (Bohn et al., 1985). Total P and WEP concentrations of the organic sources were greatest in Boca Raton biosolids (TP = 47.3 g kg^{-1}; WEP = 5.52 g kg^{-1}), representative of the high end of P concentrations spectrum in biosolids produced nationally (Kirkham, 1982; USEPA, 1995). The Boca Raton material is produced via “high rate activated sludge” process similar to a biological P removal (BPR) process and the greater total P concentration and P lability were, thus, expected (O’Connor et al., 2004). The TP concentrations of biosolids produced nationally can vary from <1g kg^{-1} to >140g kg^{-1} dry weight basis (Keeney and Walsh, 1975; Dowdy et al., 1976; Sommers, 1977), but typically are 10 g kg^{-1} to 50 g kg^{-1} (Kirkham, 1982). The TP concentrations of forty-one biosolids used by Brandt et al. (2004) ranged between 3 g kg^{-1} and 40 g kg^{-1}. Thus, the Boca Raton biosolids represents the greater soluble P member of the biosolids likely to be land-applied in FL, whereas the Pompano biosolids (TP = 26.2 g kg^{-1}; WEP = 1.12 g kg^{-1}) represents the moderate water soluble P members in the spectrum. Total Al + Fe concentrations for the Boca Raton biosolids (33 g kg^{-1}), and the Pompano (42 g kg^{-1}) biosolids are common values for biosolids not stabilized with Fe or Al salts (O’Connor et al., 2004).

Manure had the least total P concentration (25.3 g kg^{-1}), but a greater portion of the manure P was water soluble P than in the biosolids. The Boca Raton biosolids contained nearly five times more soluble WEP (5.52 g kg^{-1}) than the Pompano biosolids (1.16 g kg^{-1}), and about the same (4.57 g kg^{-1}) as the poultry manure. However, among the organic sources, the percent of TP that is water extractable (PWEP) was greatest in manure (18%) followed by Boca Raton biosolids (11%), and least in Pompano biosolids (4%).

Table 2-1. General chemical properties of amendments (P-sources and the water treatment residual (Al-WTR)) used for the glasshouse, rainfall simulation, and field studies.

Parameters (units)	<---------------------P-source------------------->				Al-WTR
	Poultry manure	Boca Raton Biosolids	Pompano Biosolids	TSP	
pH	7.7	7.6	7.6	5.9	5.5
C (g kg^{-1})	320	347	366	-	199
N (g kg^{-1})	27.0 ± 0.3†	50.4 ± 0.4†	43.1 ± 0.6†	-	0.7
C:N	11.9	6.9	8.5		-
% Solids	25.1± 0.1†	13.4 ± 0.04†	15.4 ± 0.1†	100	62.5 ± 2.2†
WEP (g kg^{-1})	4.57± 0.16†	5.52 ± 0.18†	1.16 ± 0.08†	175	0.03
§PWEP (%)	18.1	11.7	4.43	83.7	0.65
Total P (g kg^{-1})	25.3 ± 0.3†	47.3 ± 2.3†	26.2 ± 0.2†	209	2.7 ± 0.7†
Total Al (g kg^{-1})	0.9 ± 0.1†	9.3 ± 0.4†	9.2 ± 0.4†	10.0	98.7 ± 5.4†
Total Fe (g kg^{-1})	1.5 ± 0.1†	24.3 ± 0.8†	32.8 ± 0.4†	15.7	6.1 ± 0.1†
Total Ca (g kg^{-1})	102 ± 3†	27.5 ± 1.1†	47.0 ± 0.5†	137	1.5 ± 0.1†
Total Mg(g kg^{-1})	5.8 ± 0.2†	10.0 ± 0.5†	4.1 ± 0.1†	6.2	0.40 ± 0.02†
‡Oxalate Ca (g kg^{-1})	-	0.06 ± 0.0†	0.05 ± 0.0†	-	0.33 ± 0.01†
Oxalate Mg (g kg^{-1})	4.2 ± 0.1†	9.7 ± 0.0†	3.7 ± 0.2†	-	0.36 ± 0.01†
Oxalate P (g kg^{-1})	12.7 ± 0.0†	34.0 ± 0.9†	20.4 ± 0.1†	186	2.3 ± 0.0†
Oxalate Fe (g kg^{-1})	0.7 ± 0.0†	19.4 ± 0.5†	24.7 ± 0.2†	11.0	4.8 ± 0.3†
Oxalate Al (g kg^{-1})	0.2 ± 0.0†	8.9 ± 0.6†	9.2 ± 0.0†	6.9	95.1 ± 1.3†
¶PSI	-	1.44 ± 0.02†	0.7 ± 0.02†	-	0.02 ± 0.0†
††APSC (g P kg^{-1})	-12.6	-30.9	-16.8	-184	14.5

† Means of three samples ± standard deviation
‡ 0.2 M oxalate extractable
§ Percentage water extractable P (PWEP) = [(WEP mg kg^{-1}) / (Total P mg kg^{-1})]*100
¶ Phosphorus Saturation Index = [oxalate-P / oxalate-Fe + oxalate-Al (in moles)]
†† Amendments P saturation capacity = (0.15 – PSI)* [oxalate-Fe + oxalate-Al (in moles)]*31

The PWEP values of the organic sources can reflect the chemical compositions, especially the total and oxalate P, Al and Fe concentrations. The Boca Raton biosolids, a BPR material with associated greater P and smaller Al and Fe concentrations, had greater P solubility, and hence PWEP than Pompano biosolids (with smaller P and greater Al and Fe concentrations). The Al and Fe concentrations were smaller in manure than in the two biosolids, but the Ca concentration of poultry manure was greater than in the biosolids, reflecting Ca-rich additives in animal feeds (Barnett, 1994). Thus, P chemistry in manure is likely controlled by Ca-P compounds that are more soluble at the soil pH (pH ~5.5) than the Fe and Al-P compounds that tend to dominate biosolids P chemistry. The greater oxalate P and smaller oxalate Fe and Al concentrations of the Boca Raton biosolids resulted in a greater PSI = 1.44 and, hence, greater P solubility expected than in the Pompano biosolids (PSI = 0.7). A PSI of 1.1 was identified as a critical value in a glasshouse leaching study by Elliott et al. (2002b). Biosolids with PSI >1.1 resulted in much greater P leaching than those with PSI values <1.1. Biosolids PSI values are consistent with the WEP and PWEP values (Boca Raton biosolids PSI = 1.44, WEP = 5.52 g kg^{-1}, PWEP = 11%; Pompano biosolids PSI = 0.7, WEP = 1.16 g kg^{-1}, PWEP = 4%), and suggest greater mobility of P in the Boca Raton biosolids than in Pompano biosolids. The PSI index is not applicable to manure and TSP, where P chemistry is expected to be controlled by Ca rather than Al and Fe (Elliott et al., 2002b). Total and oxalate Al and Fe concentrations were smaller in manure than in the two biosolids, but the Ca concentration was greater than in the biosolids. The WEP and PWEP values could serve as relative measures of solubility of the P-sources, irrespective of the P chemistry dominance. The variations in the two measures of P solubility of the P-sources support the need for a coefficient that relates the P losses to the P-source solubility, irrespective of the P chemistry dominance. Total P and N concentrations were greatest in Boca Raton biosolids and least in poultry manure.

The Al-WTR was slightly acidic (pH = 5.5) and dominated by Al (157 g kg^{-1}), more than 90% (145 g kg^{-1}) of which was amorphous (0.2M ammonium oxalate extractable; McKeague et al., 1971). The total Al value (157 g kg^{-1}) was close to the range for typical Al-WTR (50- 150 g

kg^{-1}, ASCE, 1996). The WTR also contain significant P and Fe concentrations, ~90% of which were amorphous. Previous studies based on WEP and PWEP of WTR materials, showed that most of the P was not soluble, and the material served as a sink rather than as a source of P (O'Connor et al., 2002a). The very small PSI (0.02) of the WTR established its great P sorption capability. Also the positive APSC value of the WTR (21g kg^{-1}) identifies the material as P sink, in contrast to the negative values (-12.6 to -184 g kg^{-1}) in the biosolids, manure, and TSP.

Oxalate extractable P, Fe, and Al are usually associated with the amorphous phase of the particles. Oxalate extractable Fe + Al concentration in the Boca Raton biosolids was 28 g kg^{-1}, and 34 g kg^{-1} for the Pompano biosolids, well within the typical range (10-80 g kg^{-1}) for biosolids (O'Connor et al., 2000). The sum of inorganic sequential P fractionation values was ~ 70% of total P (Table 2-2), was close to the oxalate-P values, and typical of biosolids produced nationally (Wolf and Baker, 1985).

The NaOH-P (measure of Fe- and Al-associated forms) was the dominant fraction for the Boca Raton, and Pompano biosolids, as well as the Al-WTR (Table 2-2). The readily available P pool, KCl-P, varied among the different P-sources and was approximately one third of the total inorganic P of the Boca Raton biosolids and the poultry manure ("high soluble P" sources), but only 6% of the total inorganic P of the Pompano biosolids ("moderate soluble P" source). The P sorption properties of the WTR resulted in a very low KCl-P value, which represented only 0.3% (19 mg kg^{-1}) of the total P, thus establishing the material as a P sink rather than as a P-source.

Chemical characteristics of the native Immokalee fine sand collected from the field site are given in Table 2-3. The three soil horizons are acidic (pH ~ 5.5), and relatively low in organic carbon, ranging from 17 g kg^{-1} in the B_h horizon to 3 g kg^{-1} in the E horizon and 12 g kg^{-1} in the

A horizon. The top soil was P-deficient (M-1P < 10 mg kg^{-1}), however the Bh had greater plant available P (M-1P = 12 mg kg^{-1}).

Table 2-2. Phosphorus characteristics of the amendments (P-sources and water treatment residual (Al-WTR) used for the studies (values expressed in g kg^{-1})

Source	[‡]ISP	[§]WEP	Sequentially extracted P				Total P	Organic P (% of TP)
			KCl-P	NaOH-P	HCl-P	Inorganic P		
Poultry Manure	[†]3.90 ± 0.12	4.57 ± 0.16	3.91 ± 0.01	0.1 ±0.00	7.1 ±0.2	11.1 ±0.5	19.1 ±0.2	37
Boca Raton Biosolids	6.76 ± 0.02	5.52 ± 0.18	9.15 ± 0.02	11.7 ±0.07	8.2 ±0.8	29.1 ±0.7	34.7 ±0.3	4
Pompano Biosolids	2.30 ± 0.02	1.16 ± 0.08	1.14 ± 0.03	9.1 ±0.55	7.4 ±0.08	17.6 ±0.14	24.5 ±0.05	24
Bradenton Al-WTR	0.29 ± 0.04	0.03 ± 0.00	0.019 ± 0.00	4.0 ±0.11	0.4 ±0.04	4.4 ±0.14	5.6 ±0.04	28

[†] Means of three samples ± standard deviation (for all data except % organic-P)
[‡] Iron strip extractable P
[§] Water extractable P
[¶] Mehlich 1 extractable P

Soil Characterization

Total P values ranged from 7.9 mg P kg^{-1} (E horizon) to 24.5 mg P kg^{-1} for both the A and B_h horizons. The oxalate-P values of the B_h horizon (23.8 mg kg^{-1}) were, however, greater than in the A horizons (10 mg kg^{-1}). The E horizons contained the least oxalate-P values (3.8 mg kg^{-1}). More than 95% of Bh-horizon P is amorphous, whereas <50% amorphous P is observed in A and E-horizons. This was similar to the trend of the oxalate-extractable Al values, which showed that the B_h horizon had the greatest amount (970 mg kg^{-1}), versus 55 for the A and 16 mg kg^{-1} for the E horizon (Table 2-3). Greater oxalate extractable Fe (62 mg kg^{-1}) was found in the A horizon than in the Bh horizon (39 mg kg^{-1}, Table 2-3).

Table 2-3. Immokalee soil general chemical properties† measured in 2001 from Kirton Ranch field study

	Horizons		
	A (0-10cm)	E (~ 20 -30 cm)	B_h (75-85cm)
pH	5.5	5.9	5.1
Total P (mg kg $^{-1}$)	24.5 ± 5.46	7.9 ± 4.6	24.5 ± 11.3
Total Al (mg kg $^{-1}$)	106 ± 23.3	33.6 ± 7.55	1280 ± 770
Total Fe (mg kg $^{-1}$)	101 ± 39	38.5 ± 6.21	94.8 ± 23.2
Oxalate‡ P (mg kg $^{-1}$)	10.0 ± 2.95	3.76 ± 2.76	23.8 ± 13.7
Oxalate Al (mg kg $^{-1}$)	54.8 ± 6.74	15.8 ± 5.35	970 ± 418
Oxalate Fe (mg kg $^{-1}$)	61.7 ± 8.52	13.0 ± 5.98	39.0 ± 5.08
Mehlich 1-P (mg kg $^{-1}$)	7.03 ± 6.54	1.88 ± 1.33	12.1 ± 12.8
KCl-P (mg kg $^{-1}$)	3.87 ± 0.78	0.77 ± 0.32	3.31 ± 0.52
NaOH-P (mg kg $^{-1}$)	9.87 ± 1.23	5.49 ± 1.02	21.3 ± 3.2
HCl-P (mg kg $^{-1}$)	3.78 ± 1.02	3.14 ± 0.88	4.56 ± 1.10
Fe-strip-P (mg kg $^{-1}$)	9.6 ± 0.11	6.3 ± 0.12	16.4 ± 0.25
DPS§ (%)	20.6	29.7	4.16
SPSC¶ (mg P kg^{-1})	4.56	0.04	147

† Means of six samples ± standard deviation
‡ 0.2 M oxalate extractable
§Degree of Phosphorus Saturation = [oxalate P / oxalate Fe + oxalate Al (in moles)]*100
¶ Soil P saturation capacity (SPSC) = $[(0.15\text{-PSR})*(Al_{ox} + Fe_{ox})]*31$
Where PSR (Phosphorus Saturation Ratio) = $[(P_{ox})/(Al_{ox} + Fe_{ox})]$

The small DPS value of Bh-horizon soil (4.16%) reflects the greater amorphous Al concentration. The DPS value of the A-horizon (20.6%) was also below the 25% threshold DPS suggested for Florida soils (Nair et al., 2004) indicating that the surface horizon is not impacted with excess P. Despite the low P concentrations of the E-horizon, the DPS exceeded the threshold value because of relatively low Al and Fe concentrations and, hence, low P sorption. The data suggest that P leached into the E-horizon would move freely through. As expected, soil phosphorus storage capacity (SPSC) values vary inversely with DPS values, and the interpretation is similar to that offered for DPS values. The top soil used for the glasshouse and the rainfall simulation studies had low extractable P values (M-1P, WEP and ISP), which were similar to values for the sample taken from the A-horizon in the field (Table 2-4).

Table 2-4. General chemical properties of the Immokalee soil (0-5cm) used for glasshouse and rainfall simulation studies.

Parameters (units)	Value
pH	5.5
EC (µs cm^{-1})	323
C (g kg^{-1})	†12.0 ± 0.1
Mehlich 1-P (mg kg^{-1})	6.40 ± 0.35
WEP (mg kg^{-1})	2.88 ± 0.19
Fe-strip-P (mg kg^{-1})	3.11 ± 0.48
Total P (mg kg^{-1})	24.5 ± 2.1
Total Al (mg kg^{-1})	88.4 ± 4
Total Fe (mg kg^{-1})	107 ± 20
Total Ca (mg kg^{-1})	449 ± 8
Total Mg (mg kg^{-1})	36 ± 3
Oxalate P (mg kg^{-1})	22.6 ± 1.6
Oxalate Al (mg kg^{-1})	49.8 ± 3.6
Oxalate Fe (mg kg^{-1})	96.0 ± 5.3
Oxalate Ca (mg kg^{-1})	34.8 ± 2.5
Oxalate Mg (mg kg^{-1})	20.4 ± 1.8
DPS‡ (%)	41.0
SPSC§ (mg P kg^{-1})	-6.05

† Means of three samples ± standard deviation (for all data except pH, EC, DPS, and SPSC)
‡Degree of Phosphorus Saturation [oxalate-P / 0.5*[oxalate-Fe + oxalate-Al (in moles)]*100
§Soil P saturation capacity = (0.15 –PSR¶)* [oxalate-Fe + oxalate-Al (in moles)]*31
¶Phosphorus Saturation Ratio = [oxalate-P /(oxalate-Fe + oxalate-Al (in moles)]

Soil M-1P of <10 mg kg^{-1} is considered very low for agronomic crops, including bahiagrass (Kidder et al., 2002). The low P makes the soil suitable for the P response experiment, and for testing impacts of different P-sources and WTR application rates on plants and P losses. Plant response to added P and other treatments should be easily identified in an initially P deficient soil. The pH 5.5 coincides with the so-called "target" pH for bahiagrass, thus, making it suitable for the growth of bahiagrass (Hanlon et al., 1990). Contributions of the native soil to P losses are expected to be negligible, making treatment impacts on the runoff and leachate P more pronounced and more easily identified in the rainfall simulation study.

CHAPTER 3
AGRONOMIC IMPACTS OF LAND APPLIED WTR AND DIFFERENT P-SOURCES

Introduction

Land application of organic amendments is supported by USEPA 40 CFR Part 503 (USEPA, 1995) and other environmental agencies worldwide as long as the amendments are applied at agronomic rates based on crop N-requirements (N-based). However, the N-based application of manures and biosolids often supplies P to soil in excess of that removed by plants. The excess P accumulates in the soil (Pierzynski, 1994; Maguire et al., 2000), and is often subject to offsite migration to surface waters. Amendment application rates based on crop phosphorus needs (P-based) dictate substantially lower P-source application rates and less potential for P loss. The lower rates, however, are economically unattractive because they require supplemental N-fertilizer application, larger disposal areas to accommodate the same amount of amendments, and higher cost to transport the materials to additional land from outside sensitive watersheds.

Phosphorus pollution of waters is a major concern in Florida and other coastal plain soils with low-P retention capacities. Low P-retention, coupled with the characteristic flat topography and interception of shallow ground waters by discharge systems, favors the eventual entry of leached P to surface water bodies. Thus, control of excess soil soluble P resulting from amendments applications that exceed plant needs and in P-impacted soils is very important in Florida.

Among the measures being suggested to reduce environmental P losses is the use of Al-rich water treatment residuals (WTR) to increase affinity for soluble P. Possible negative impacts of WTR land application include excessive immobilization of plant-available soil P and Al toxicity. Severe P-deficiency symptoms were noted by Heil and Barbarick (1989) with 25 g WTR kg^{-1} soil planted to sorghum-sudangrass [*Sorghum bicolor* (L.) *Moench Sorghum X drummondii* (Steudel) *Millsp.* Chase]. Ippolito et al. (1999) also found decreased P concentrations in blue grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.) with increasing WTR rates. Rengasamy et al. (1980) reported reduced P uptake in maize (Zea mays L.) with WTR addition, while Elliott and Singer (1988) and Bugbee and Frink (1985) found reduced P concentrations in tomato (Lycopersicon esculentum L.) and lettuce (Lactuca sativa L.) grown in WTR-amended potting media. Exchangeable P was measured in soils amended with sewage biosolids and WTR (Naylor and Carr, 1997). The Al-WTR (116g Al kg^{-1}) amendment reduced exchangeable P level in the soils, but did not limit plant growth, suggesting that WTRs may be useful for reducing P solubility in high P soils without inducing a P deficiency. Rengasamy et al. (1980) also reported improved aggregation by adding air-dried Al-WTR to soils at rates of 2 and 20 g kg^{-1}, but the high application rate decreased germination and P uptake by maize, *zea mays*. Yields of fescue grass (*Festuca ovina* 'glauca') grown in the greenhouse decreased with increasing Al-WTR application rates (0, 10, 20, and 40 g WTR kg^{-1}) to soil and attributed to reductions in plant-available P due to excessive P immobilization. The deficiency was corrected with supplemental P fertilizer (Lucas et al., 1994). The possibility of P deficiency, reduced crop yield, and Al phytotoxicity following land application of WTR, calls for an in-depth study into the best management of the amendment that will not induce negative agronomic impacts.

Solubility of WTRs rich in amorphous Al and, hence, dissolution of P, adsorption of P and speciation and distribution of other chemicals can be affected by soil pH. Soluble aluminum is the most common source of phytotoxicity in acid soils (Arkin and Taylor, 1981), and Al toxicity is one of the yield-limiting factors identified in acid soils. The Al toxicity in soil could cause shallow rooting, drought susceptibility and poor soil nutrients usage by plants. The aluminum species, responsible for the phytotoxicity, Al^{3+}, typically is a small fraction of the total aluminum in the soil solution. Cornell Recommends (1992) suggest that a soil test (e.g., Morgan) aluminum value in the range of about 1 to 100 kg/ha is normal, with higher values being excessive, but not necessarily phytotoxic. Indeed, many soils exceed 100 kg ha^{-1} soil test (exchangeable) aluminum and continue to remain productive. Aluminum concentration can be sufficiently high in acid soils with pH values < 5.5 to be toxic to plants. Alum-treated litter or alum hydrosolids (similar to WTR) have neutral or alkaline pH, and the resulting insoluble Al oxides do not release toxic Al or produce acidity in soil or aqueous systems (Peters and Basta, 1996). The lack of Al toxicity needs to be confirmed for other soils, including Florida soils with pH values ≤ 5.5.

Another aspect of organic amendments usage that needs consideration is the effectiveness as P-sources for agronomic benefits. A 50% effectiveness of biosolids-P compared with fertilizer-P was suggested by USEPA process design manual (USEPA, 1995), while 40% was recommended by Ontario, Canada regulations (OMEE, 1996). Short-term studies have shown biosolids-P phytoavailability can vary from ~0% to 100% depending on properties of the sources (de Haan, 1981; Hani et al., 1981; Smith et al., 2002; O'Connor et al., 2004). Additional study is needed for longer periods in Florida sands and in the absence of leaching. The longer period of the study will allow determining how the relative phytoavailability changes with time (residual effects), and differences in P accessible by plants from each P-sources over time will be prevented when no leaching is allowed.

The purpose of this study was to evaluate agronomic impacts of various P-sources and WTR applied to Florida sands. Results are expected to enhance consistent and accurate fertilization decisions for Florida sands receiving different sources of P and WTR and help avoid reduced crop yields due to excessive P immobilization and Al toxicity. We hypothesized that:

1. (a) P-based rates of different organic sources of P, without WTR, optimize agronomic yield and P uptake.

   (b) N-based rates of different organic sources of P, with WTR, optimize agronomic yields and P uptake.

2. Amendment rates (P-sources and WTR rates) selected in (1) that optimize P uptake also minimize soil soluble P.

3. Organic sources of P vary in P bioavailability

4. Land application of Al-WTR increases plant Al concentrations.

The main objective of the study was to evaluate the agronomic impacts of different P-sources and WTR, and the specific objectives of the studies were to:

1) Determine the rates of WTR and organic sources of P that optimize agronomic benefits, while minimizing soil soluble P that could pose environmental hazards.

2) Evaluate the impacts of selected amendments (WTR and organic sources of P) on soil P-sorption properties.

3) Determine the relative P phytoavailabilities of different P-sources.

4) Evaluate the impacts of Al-WTR on plant Al concentrations.

Materials and Methods

Experimental Procedure

Each of the four P-sources (poultry manure, Boca Raton biosolids, Pompano biosolids, and TSP) was applied to the P-deficient Florida soil at two rates (N and P plant requirement basis). Each treatment also received WTR applications at 3 rates (0, 10 and 25 g kg^{-1} oven dry basis). Thus, the glasshouse pot experiment was a 4X2X3 factorial experiment with 1 control and arranged in randomized complete block design with 3 replicates. Soil (8.5 kg) and appropriate amounts of the amendments were weighed and thoroughly mixed in a polythene bag. Water was added to bring the mixture to field capacity, and the treated soils allowed to equilibrate for one week with daily mixing.

Weights of P-sources needed to supply the equivalent of 44 kg total P ha^{-1} (P-based application rate) and 179 kg plant available nitrogen (PAN) ha^{-1} (N-based rate), as recommended for bahiagrass (Kidder et al., 1998), were calculated from total P and N concentrations of the P-sources. Mineralization rates of 40% of total N in biosolids and 60% of total N in manure were assumed in the calculation, based on previous experience in similar studies (O'Connor and Sarkar, 1999; O'Connor et al., 2004). Deficits in PAN (for the P-based rates) between the N provided by various P-sources applied and the target PAN levels were calculated and supplied by split (monthly) applications of NH_4NO_3. Twice the P applied in P-based rates (88 kg total P ha^{-1}) was used as P supplied by TSP at N-based rate. The intent was to fix the P supplied at the P-based rates, whereas the P supplied by the N-based rates varied with P-sources and all treatments received equal amounts of N (179 kg PAN ha^{-1}). An amount (1.8 g, equivalent to 444 kg ha^{-1}) of potassium-magnesium sulfate ("Sul-Po-Mag": 22% S, 18% K, and 11% Mg) was added to each treatment to provide adequate and uniform S, K, and Mg. Amounts of NH_4NO_3 needed to supplement the control treatment to 179 kg PAN ha^{-1} were also added to ensure that all pots had adequate readily available N.

Samples of the amended soils were taken after the one week of equilibration in June 2004 for analysis (Time zero samples). The remaining soil was placed in a plastic pot (6.5×10^3 cm^3) and planted with first bahiagrass at a depth of 3 mm and seeding rate of 7g per pot. The soil surface of each pot was covered with filter paper to reduce evaporation, and moistened daily, until seed germination. After germination, the papers were removed and soil wetted daily, and returned to initial weight weekly. Water with pH adjusted to 5.0 was used throughout the study to eliminate poor growth of bahiagrass in high pH soil. There was non-uniform germination of the bahiagrass despite the careful nurturing described, and missing areas of the pots were reseeded after one week. Because of the problems encountered during establishment of the plants, the first harvest was done 36 days after removing the filter papers, whereas subsequent harvests occurred monthly. Harvesting was at a height of 5 cm above soil surface with scissors or electric clippers. Cuttings were placed in a pre-weighed labeled paper bag for drying to constant weight at 65 ^{0}C, and dry matter (DM) weight determined as the differences between the dried paper bags with cuttings and pre-weighed empty bag. After each harvest, plant pots were weighed and watered as necessary after adding the supplemented N (split applied) as necessary to return to initially determined pot weights. The randomized pots were shifted by a position twice weekly to minimize positioning advantage in the glasshouse.

All treatments were supplied with adequate N and other nutrient elements except P throughout the study and each pot planted with pasture grasses continuously for fifteen months (bahiagrass during the warm season and ryegrass during the cold season). The order of grass planted was bahiagrass (*paspalum notatum* Fluggae) for six months (between June 2004 and December 2004), ryegrass (*Lolium perenne* L.) for five months (between December 2004 and May 2005), and a second bahiagrass cropping for four months (between May 2005 and September 2005). The extended growing season allowed studying the residual effect of the WTR, the P-sources and source application rates on agronomic P use efficiency. Also, mining the soil P for extended periods will ensure P deficiency, which is often accompanied by Al toxicity (if it is an issue) especially when soil pH is below 5.5.

A total of four monthly cuttings were obtained from the first bahiagrass cropping. After the fourth harvest of the first bahiagrass cropping, soil samples were taken in December 2004 from the center of each pot using an auger of 5 cm diameter and extending to the bottom of the pot. The hole created was filled with time zero soil preserved for that purpose. Each pot was then planted with ryegrass (3g seed pot^{-1}), a cool season grass. Continuous planting is necessary to evaluate the residual effects of the amendments. Soil obtained after the fourth bahiagrass harvest served as time zero soil for the ryegrass cropping for analysis purpose.

The management of the ryegrass was the same as for the bahiagrass, and the grass was harvested three times (approximately monthly). Additional soil samples were taken in May 2005 after the ryegrass final harvest. Previous sampling points had been marked to prevent sampling the same spot twice. The hole created was again filled with soil preserved from the initial time zero soil samples of each treatment. Another bahiagrass crop was then planted with similar management for four months (3 harvests) between July and September 2005. Final soil samples were taken in September 2005 and the experiment terminated. No leaching was allowed throughout the study so as to minimize P and other nutrient losses and to enhance studying the long term P phytoavailability of the different P-sources.

Soil and Plant Analysis

All sets of soil samples taken during the study (in June 2004, December 2004, May 2005 and Sept. 2005) were analyzed for pH and EC (1:2 solid:solution), total recoverable P, Al and Fe (USEPA, 1986) and 0.2M oxalate extractable P, Al and Fe (Schoumans, 2000). The same procedures used for the initial soil characterization (Chapter 2) were employed. Extractable P determinations (Mehlich-1 P, WEP and ISP) were also measured as described in Chapter 2.

Dried monthly plant cuttings weighed for dry matter determinations were ground in a Wiley mill with stainless steel blades to pass a 20mm-mesh sieve and stored in airtight polyethylene containers. Ground plant samples were ashed, treated with 6M HCl, and brought to final volume with distilled water as described by Plank (1992). Phosphorus in diluted digests was determined colorimetrically (Murphy and Riley, 1962). The plant uptake (kg P ha^{-1}) was calculated as the product of P concentrations and dry matter weights. Weighted means of plant P concentrations were obtained by dividing the total P uptake by the total dry matter weight for all the harvests of each cropping.

Aluminum, Ca, Mg, and Fe concentrations in the diluted plant digests of the N-based TSP treatments were determined using ICAP to evaluate the impact of the applied WTR on the Al and elemental concentrations of the plants.

Standard QA/QC protocols were observed during the sample collection, handling and chemical analysis. For each set of samples during chemical analysis, a standard curve was constructed ($r^2 > 0.998$). Method reagent blanks were appropriately used, as well as certified standards. A 5% matrix spike of the set was used to determine the accuracy of the data obtained and another 5% of the set was used to determine the precision of the measurements (recovery ranging from 96 – 103%). Analyses that did not satisfy the QA/QC protocol were rerun.

Statistical Analysis

Soil and plant data were analyzed by analysis of variance (ANOVA), using the GLM procedure in SAS (SAS Institute, 1999). The means were separated by single degree of freedom contrast procedures or the Tukey method. Regressions of soil extractable P with plant yields, P concentrations, and P uptakes were done using SAS. All statistical analysis tests were done using a significance level of 5%.

Results and Discussion

Soil pH and EC During the Study

The pH of soil sampled during the study varied with the treatments and time (Appendix Fig. 3-1). Manure treatments were slightly basic (pH values = 7.1 to 7.4) at the N-based rate (11.1 Mg ha^{-1}) but slightly acidic (pH values = 5.6 to 6.6) at the P-based rate (1.74 Mg ha^{-1} of manure). The greater pH in manure treatments was also noted by O'Connor et al. (2000) when poultry manure was applied at 12 Mg ha^{-1} to a similar soil. The soil pH of treatments receiving other P-sources (biosolids and TSP) were acidic (4.9 -6.6) and similar to the pH of the control (4.9 – 5.7). Thus, the biosolids and TSP treatments had less impact on the soil pH than manure treatments at the N-based rate. The greater soil pH values in treatments receiving poultry manure relative to other P-sources at both P- and N-based rates may have resulted from calcium carbonate-containing additives in the poultry feeds.

Application rates of different P-sources also affected the soil pH. Greater soil pH at N-based than P-based rate was observed by contrasts for all the organic sources treatments at time zero, whereas TSP treatments showed the opposite trend, i.e., lower pH values at N-based than at P-based rates. The greater soil pH as a result of manure application at N-based rate than in other P-sources could reduce the growth of the acid tolerant bahiagrass, which has a target pH of 5.5 (Kidder et al., 2002).

Soil pH increased with increasing WTR rates for each of the P-sources applied at both N- and P-based rates. The WTR, though lower in Ca concentration, had a substantial amount of Mg, and lime added during WTR production could also raise the soil pH. Other studies (Bugbee and Frink, 1985; Codling et al., 2002) reported similar pH increases with WTR or alum sludge applied to soils. The greater soil pH at N-based rates than P-based rates at each of the WTR rates was apparently due to greater material loads at N-based rate. The materials applied at N-based rates (11.1, 10.4, and 8.66 Mg ha^{-1} for manure, Boca Raton biosolids and Pompano biosolids, respectively) were more than six times the masses applied at the P-based rates (1.74, 1.24, and 1.68 Mg ha^{-1} for manure, Boca Raton biosolids and Pompano biosolids, respectively). Thus, both WTR rate and rate of P-sources increased soil pH.

Generally, soil EC values values were greater at N-based rates than P-based rates for all P-sources tested. Also, similar EC values were observed for different P-sources at P-based rate treatments, but at N-based rate, soils treated with organic sources of P have greater EC values than mineral P-source treated soils. The soil EC values at P-based rate of all P-sources, irrespective of amount of WTR added, were similar to the control throughout the study. Generally, the EC values were greater at the N-base rates with WTR than in the control. The greatest soil EC values of each sampling period was observed at N-based rate of manure with 2.5% WTR (Appendix Table B-2), which could result from the greater soil load of the material rich in residues from poultry feeds additives especially in this study with no leaching allowed. However, the EC values were below 800 µs cm^{-1}, and hence, fall within the tolerance range of the test plants (Brady and Weil, 2002). Bahiagrass can tolerate 7500 µs cm^{-1} (Bogdan, 1977), while ryegrass is tolerant to EC value not greater than 8000 µs cm^{-1} (Brady and Weil, 2002). Most importantly, there were no salt effects observed on the growth of the plants throughout the study.

Soil Phosphorus During the Study

Both measures of soil soluble P, WEP and ISP, exhibited similar trends with applied treatments, and clearly reflected WTR treatment effects. Soil WEP was affected by P-source, source application rates, and WTR rates (Fig. 3-1).

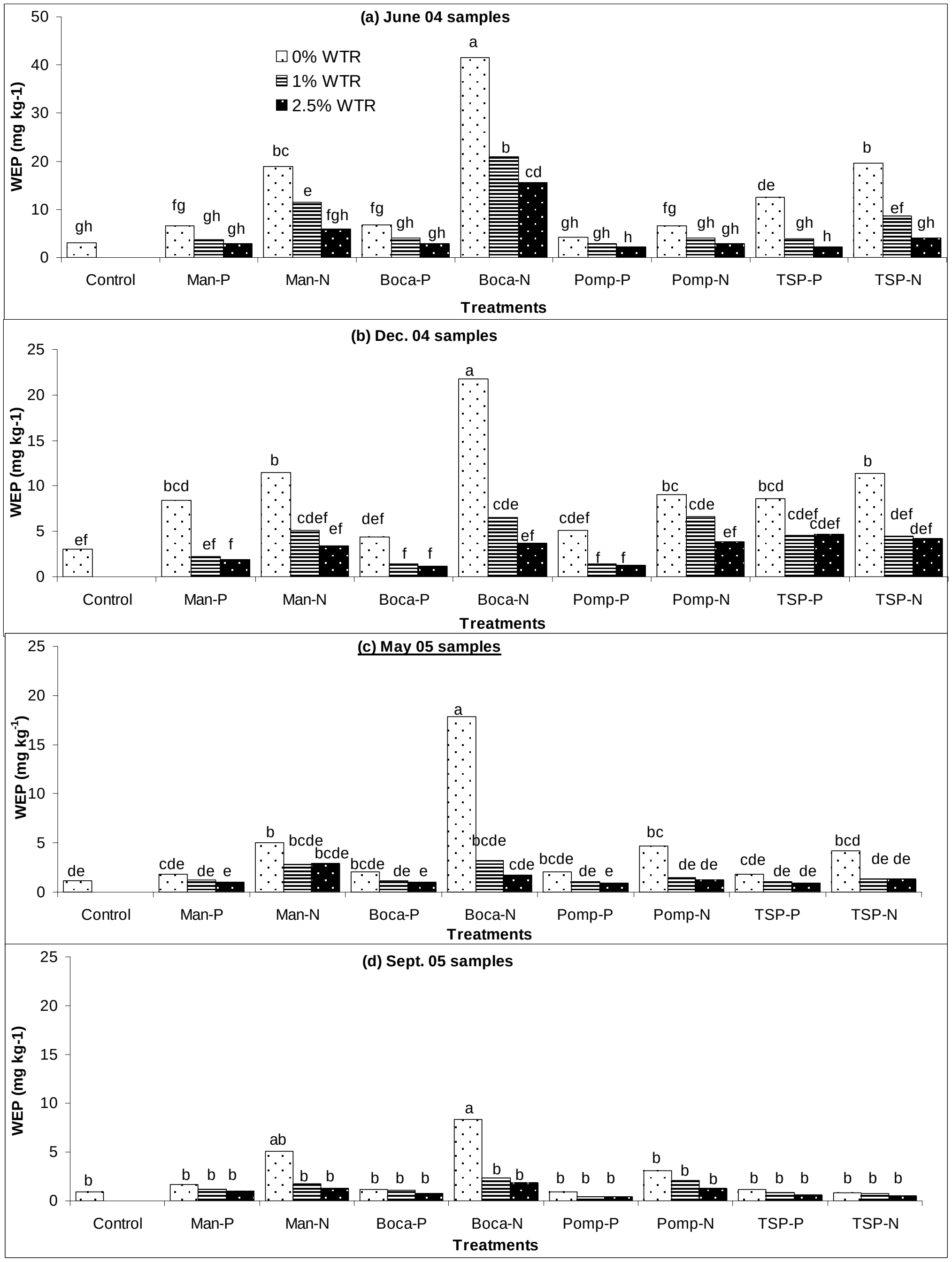


Figure 3-1. Effects of P-source, source application rates, and WTR rates on water extractable P (WEP) values of soil samples taken during the glasshouse study. Note the differences in scales of y-axis. (Treatments with the same letter are not different at 5% significant level by Tukey test)

Adding WTR reduced soil WEP values of samples taken throughout the study (June '04, Dec. '04, May '05 and Sept.'05) for all P-sources and at both source application rates. In the absence of WTR, the absolute WEP values were greater at the N-based than at the P-based rate of all P-sources. However, the presence of WTR resulted in similar soil WEP values for soils at both source rates. Thus, the potential hazards of excess soil soluble P in soils amended at N-based rates could be reduced to that observed at P-based rates by WTR addition. The only exception to this WTR effect was the time zero sample at 1%WTR, where soil WEP values was greater at N-based than P-based rate of the TSP and indicates 1% WTR may not be sufficient to sorb and mask the excess P at the greater P rate of the highly soluble TSP treatments. The greater solubility of TSP makes it accessible to sorption especially at higher rates of WTR and, hence, resulted in similar WEP values of the two application rates of TSP at 2.5% WTR. Also in samples taken at time zero, WEP values of soils treated with manure and Boca Raton biosolids were greater at N-based rates than at P-based rates at all three levels of WTR. Thus, the excess P associated with applying organic sources of P at higher rates (N-based) was not totally masked by the added WTR. The greater P solubilities of the two P-sources applied at N-based rates may require more than 2.5% WTR to reduce the soluble P values to those at P-based rate.

Sources of P also affected soil WEP values during the study. The effect of P-sources on soil WEP values could be isolated by considering P-based treatments (without WTR) in which equal P loads were applied from the different P-sources. At the P-based rate, and in the absence of WTR, time zero soil WEP values were greater in the TSP treatment than the biosolids treatments and in Boca Raton biosolids treatment than in Pompano biosolids treatment. The trend of the soil WEP values tracked well with the solubility of the P-sources as indicated by their WEP and PWEP values, which were greater in TSP than in biosolids and in Boca Raton biosolids than in Pompano biosolids. Thus, the soil soluble P values depend on solubility of the P-sources applied. However, the effects of P-sources on WEP values were not observed when WTR was applied at P-based rates.

At N-based rates, the soil WEP values were greater in Boca Raton biosolids treatment than in manure, Pompano, or TSP treatments, reflecting the greater P loads of Boca Raton biosolids (201 mg kg^{-1}) than other P-sources (75 – 125 mg kg^{-1}). Apart from manure and Boca Raton biosolids at N-based rate, the time final soil WEP values were similar for the different organic source of P, irrespective of P-source application rate and rate of WTR (Fig. 3-1). The WEP values of Pompano biosolids (N-based, without WTR) were similar to, or lower than, values observed at P-based rate of other P-sources without WTR. This suggests that moderate water soluble P-source such as Pompano biosolids could be applied at N-based rates without greater P hazards than observed at the P-based rate of other P-sources.

The effects of treatments on soil ISP values were similar to the WEP trends, and the slight difference could be traced to more P being extracted as ISP than WEP (Table 3-1). For instance, in time zero soils, ISP determination was able to differentiate between N-, and P-based rates in all the P-sources (including Pompano biosolids) at 1% and 2% WTR, which were shown to have similar WEP values. Thus, soil ISP indicates more P is available for plants at N-based rates than at the P-based rate, whether WTR is added or not. Also contrary to the trend of the WEP data, ISP values were greater in Boca Raton biosolids treatments than Pompano biosolids treatments at P-based rate (without WTR) throughout the study. The data reflected greater soluble P and, hence, plant available P expected from Boca Raton biosolids than Pompano biosolids treatments. The data suggest that the ISP technique predicts bioavailability better than the WEP determination. The ISP has been shown to be a good measure of bioavailable P

(Sharpley, 1993a, b). Apart from the few differences in the two measures of time zero soil P, both WEP and ISP values were generally similar for the P-based treatments for the different P-sources when 2.5%WTR was applied. They also both agree that, at N-based rates and at all levels of WTR, soil P is greater in Boca Raton biosolids than in other P-sources.

Table 3-1. Effects of P-source, source application rates, and WTR on iron strip P (ISP) values of soil samples taken during the glasshouse study. All concentration values are expressed in mg kg^{-1} soil.

P-source	P-source rate	WTR rate (Oven dry %)	<------------Sampling periods†------------->			
			June ‘04	Dec. ‘04	May ‘05	Sept. ‘05
Control	--	--	3.11 ^{h}	3.87 ^{g}	1.35 ^{c}	1.82 ^{h}
Manure	P-based	0	9.04 ^{ef}	8.16 ^{efg}	2.23 ^{c}	6.19 ^{efgh}
		1	6.04 ^{fgh}	4.91 ^{fg}	2.12 ^{c}	2.92 ^{fgh}
		2.5	3.08 ^{gh}	4.37 ^{g}	1.78 ^{c}	2.37 ^{gh}
	N-based	0	23.3 ^{c}	25.5 ^{b}	11.7 ^{bc}	23.8 ^{b}
		1	16.3 ^{d}	13.1 ^{cde}	8.12 ^{bc}	11.2 ^{cde}
		2.5	11.7 ^{e}	9.26 ^{defg}	7.77 ^{bc}	7.32 ^{defgh}
Boca Raton Biosolids	P-based	0	7.37 ^{efg}	8.00 ^{efg}	2.90 ^{bc}	6.04 ^{efgh}
		1	4.09 ^{fgh}	5.24 ^{fg}	2.24 ^{c}	3.26 ^{fgh}
		2.5	3.79 ^{gh}	4.28 ^{g}	1.90 ^{c}	2.27 ^{h}
	N-based	0	52.4 ^{a}	32.7 ^{a}	26.0 ^{a}	31.1 ^{a}
		1	35.9 ^{b}	17.5 ^{c}	10.4 ^{bc}	15.7 ^{c}
		2.5	20.9 ^{cd}	11.1 ^{cdef}	11.8 ^{bc}	9.15 ^{cdefg}
Pompano Biosolids	P-based	0	4.34 ^{h}	6.33 ^{fg}	3.46 ^{bc}	4.34 ^{fgh}
		1	3.32 ^{h}	4.54 ^{fg}	2.78 ^{bc}	2.57 ^{fgh}
		2.5	2.72 ^{h}	4.00 ^{g}	2.12 ^{c}	2.01 ^{h}
	N-based	0	11.9 ^{e}	15.0 ^{cd}	14.0 ^{b}	13.2 ^{cd}
		1	7.96 ^{efg}	8.38 ^{defg}	4.75 ^{bc}	6.42 ^{efgh}
		2.5	5.43 ^{fgh}	6.08 ^{fg}	3.79 ^{bc}	4.10 ^{fgh}
TSP	P-based	0	10.4 ^{e}	7.43 ^{efg}	2.69 ^{bc}	5.47 ^{efgh}
		1	4.47 ^{fgh}	4.68 ^{fg}	1.78 ^{c}	2.70 ^{fgh}
		2.5	3.02 ^{h}	3.98 ^{g}	1.80 ^{c}	2.00 ^{h}
	N-based	0	20.8 ^{cd}	11.2 ^{cdef}	5.33 ^{bc}	9.26 ^{cdef}
		1	12.4 ^{e}	5.54 ^{fg}	3.24 ^{bc}	3.58 ^{fgh}
		2.5	6.97 ^{fgh}	4.83 ^{fg}	8.10 ^{bc}	2.83 ^{fgh}

†Means (n = 3) of treatments during the same sampling period follow by the same letter are not different at 5% significant level by Tukey test.

Also, similar to the soil WEP data, there were reductions of time zero soil ISP values with addition of WTR at both P- and N-based rates. The only exception was Pompano biosolids treatments at P-based rate. However, in soil samples taken between Dec. 2004 and Sept. 2005 when the study was terminated, similar ISP values were observed in all P-sources treatments at the P-based rate, irrespective of WTR rate. The similar soil ISP values show the ability of the extractant and, hence, the potential of plants to desorb some WTR-sorbed P especially when P is limiting, as observed during the study of treatments residual effects at P-based rates. On the other hand, at the N-based rate, soil ISP decreased with increased WTR for all P-sources in most cases. These data suggest that not all WTR-sorbed P is accessible to the iron strip extractant, hence, if the extractant adequately predict plant available P, not all WTR-sorbed P will be accessible to the plants.

The soil M-1P values were either similar or increased with increasing WTR, and indicate the solubilising effect of the acidic extractant (Table 3-2). The acidic extractant ($pH < 2$) releases some WTR-sorbed P, reflected in the similar or greater M-1P values with increasing WTR rates.

Greater soil M-1P values at N-based rates than P-based rates of organic source treatments are observed in all soil samples and in TSP at time zero (but not in subsequent samples), reflecting the greater P loads at N- than P-based rates (Table 3-2). Similar M-1P values were observed for the different P-sources at P-based rate (due to similar added P), but reflected the trend of P added from different P-sources at N-based rates. The M-1P values were greatest in Boca Raton biosolids and least in TSP treatments. The P load at the N-based rate for TSP (88 kg P ha^{-1}) was smaller than the P loads from other sources, (280 kg ha^{-1} from Manure, 370 kg ha^{-1} from Boca biosolids and 233 kg ha^{-1} from Pompano biosolids) which may explain the observed smaller M-1P in the TSP than in the organic sources of P treatments. Soil M-1P reflects the soil P load, but is insensitive to the WTR-sorbed P.

Table 3-2. Effects of P-source, source application rates, and WTR on Mehlich-1P (M-1P) values of soil samples taken during the glasshouse study. All concentration values are expressed in mg kg^{-1} soil.

P-source	P-source rate	WTR (%)	June '04	Dec. '04	May '05	Sept. '05
Control	--	--	†6.40 [g]	2.93 [f]	2.24 [i]	1.40 [h]
Manure	P-based	0	15.8 [fg]	14.3 [ef]	5.93 [ghi]	4.63 [gh]
		1	23.7 [efg]	14.7 [ef]	13.6 [fghi]	10.3 [fgh]
		2.5	29.7 [efg]	19.2 [e]	20.2 [fg]	15.5 [fg]
	N-based	0	63.5 [bcd]	67.5 [abc]	54.0 [bc]	51.4 [bcd]
		1	69.5 [b]	67.5 [abc]	59.6 [ab]	55.1 [bc]
		2.5	69.3 [b]	66.1 [bc]	57.7 [b]	47.9 [cde]
Boca Raton Biosolids	P-based	0	23.7 [efg]	10.5 [ef]	6.92 [ghi]	3.81 [gh]
		1	24.8 [efg]	14.9 [ef]	14.1 [fghi]	11.3 [fgh]
		2.5	31.8 [efg]	18.4 [ef]	21.5 [ef]	16.4 [fg]
	N-based	0	164 [a]	67.9 [abc]	55.7 [bc]	48.1 [cde]
		1	147 [a]	69.6 [ab]	64.5 [ab]	68.4 [a]
		2.5	148 [a]	82.7 [a]	72.3 [a]	61.9 [ab]
Pompano Biosolids	P-based	0	16.6 [fg]	8.77 [ef]	7.50 [fghi]	4.16 [gh]
		1	20.5 [efg]	11.9 [ef]	11.4 [fghi]	10.9 [fgh]
		2.5	26.9 [efg]	17.9 [ef]	16.0 [ef]	13.6 [fgh]
	N-based	0	66.5 [bc]	48.8 [d]	35.8 [de]	35.0 [e]
		1	64.3 [bc]	49.6 [d]	50.2 [bcd]	40.9 [de]
		2.5	65.2 [bc]	52.2 [cd]	41.7 [cd]	45.4 [cde]
TSP	P-based	0	23.5 [efg]	10.7 [ef]	5.01 [hi]	4.16 [gh]
		1	24.4 [efg]	11.6 [ef]	10.4 [fghi]	12.9 [fgh]
		2.5	24.7 [efg]	15.1 [ef]	17.3 [fgh]	14.8 [fg]
	N-based	0	46.8 [bcde]	16.0 [ef]	11.2 [fghi]	7.86 [fgh]
		1	37.6 [def]	17.1 [ef]	17.1 [fgh]	15.6 [fg]
		2.5	41.2 [cdef]	19.9 [e]	16.3 [fghi]	18.9 [f]

†Means (n = 3) of treatments during the same sampling period follow by the same letter are not different at 5% significant level by Tukey test

The 0.2M oxalate extractable P (Ox-P) measures the sum of soil soluble and amorphous oxide-sorbed P forms, including a part of the WTR-sorbed P. The trends of Ox-P values of time zero and time final soil samples were generally similar (Fig. 3-2). As expected, soil Ox-P values were greater for N-based treatment than for P-based treatment reflecting the different P loads, and were similar for the P-based treatments with similar P loads. However, at N-based rate, the trend was for greater Ox-P values in biosolids than in manure treated soils, in organic source of P treatments than TSP treatment, and similar Ox-P values in the two biosolids treatments. The trend also tracked well with the trend of applied-P from the different P-sources at N-based rates, as earlier explained. The soils showed increasing Ox-P values with increasing WTR, due to P sorbed and contribution of WTR to soil P.

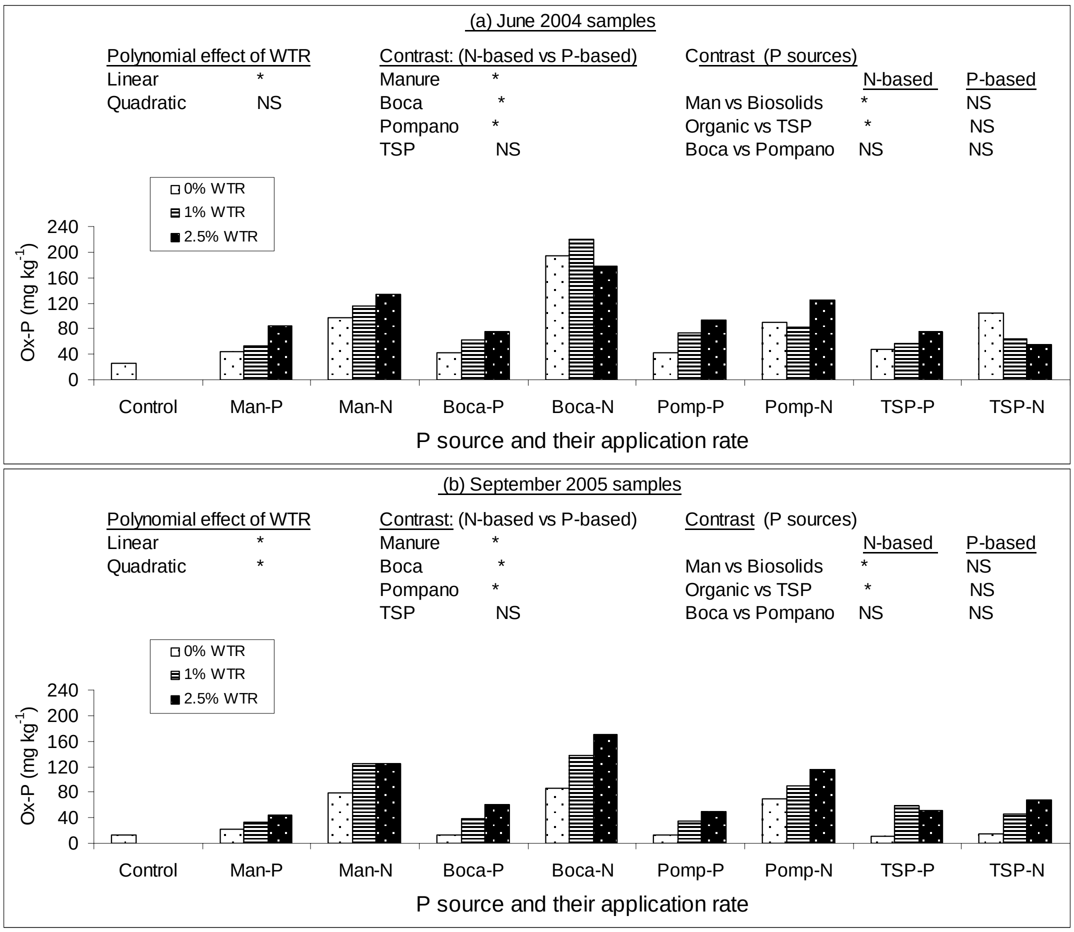


Figure 3-2. Oxalate extractable P (0.2M) values of (a) time zero and (b) time final soil samples taken during the glasshouse study

Soil Total recoverable P is a measure of the soil P load, and includes the applied-P and P from natural sources. The trend of the Total recoverable P values was similar for soils sampled at different times during the study with few differences (Table 3-3). Soil Total recoverable P values were greater for N-based treatment than for P-based treatments of the organic source of P throughout the study. The least amount of P applied as organic sources of P at N-based rates was six times the applied-P at P-based rates, which explains the greater Total recoverable P at N-based than at P-based rates. However, in TSP amended soils, the soil Total recoverable P was greater at N-based than P-based rates only in time zero soils at 0 and 1% WTR.

Table 3-3. Effects of P-sources, source application rates, and WTR on Total recoverable P values of soil samples taken during the glasshouse study. All concentration values are expressed in mg kg^{-1} soil.

P-source	P-source rate	WTR rate (Oven dry %)	Sampling periods†			
			June '04	Dec.04	May '05	Sept. '05
Control	--	--	23.6 ^{k}	22.0 ^{k}	28.3 ^{h}	12.2 ^{j}
Manure	P-based	0	40.0 ^{jk}	43.3 ^{hijk}	38.3 ^{fgh}	19.6 ^{hij}
		1	53.0 ^{ghijk}	56.3 ^{ghijk}	58.2 ^{fgh}	44.2 ^{ghi}
		2.5	77.9 ^{efg}	78.7 ^{efghi}	82.2 ^{efgh}	45.1 ^{ghi}
	N-based	0	125 ^{bcd}	111 ^{cdef}	133 ^{bcde}	78.2 ^{cde}
		1	128 ^{bcd}	133 ^{bc}	142 ^{bcd}	85.9 ^{cd}
		2.5	153 ^{b}	152 ^{bc}	144 ^{bc}	103 ^{bc}
Boca Raton Biosolids	P-based	0	46.0 ^{ijk}	35.5 ^{jk}	36.1 ^{gh}	17.9 ^{ij}
		1	61.6 ^{fghij}	52.9 ^{ghijk}	60.7 ^{fgh}	40.9 ^{ghi}
		2.5	82.1 ^{efgh}	75.8 ^{efghij}	93.7 ^{cdefg}	61.7 ^{defg}
	N-based	0	201 ^{a}	88.2 ^{defg}	131 ^{bcde}	77.0 ^{cdef}
		1	156 ^{b}	170 ^{ab}	163 ^{ab}	121 ^{ab}
		2.5	221 ^{a}	207 ^{a}	212 ^{a}	147 ^{a}
Pompano Biosolids	P-based	0	48.7 ^{hijk}	35.4 ^{defg}	38.6 ^{gh}	20.0 ^{hij}
		1	67.8 ^{fghij}	48.2 ^{ghijk}	61.0 ^{fgh}	36.4 ^{ghij}
		2.5	73.5 ^{fghij}	73.0 ^{efghij}	84.6 ^{defgh}	49.7 ^{fg}
	N-based	0	116 ^{cde}	89.9 ^{jk}	67.5 ^{fgh}	55.9 ^{efg}
		1	133 ^{bc}	113 ^{cde}	128 ^{bcde}	82.3 ^{cde}
		2.5	131 ^{bc}	126 ^{cd}	133 ^{bcde}	98.5 ^{bc}
TSP	P-based	0	54.7 ^{ghijk}	35.5 ^{jk}	32.3 ^{h}	17.3 ^{ij}
		1	49.5 ^{ghijk}	50.4 ^{ghijk}	54.8 ^{fgh}	41.3 ^{ghi}
		2.5	48.3 ^{efg}	69.2 ^{fghij}	81.6 ^{efgh}	50.1 ^{fg}
	N-based	0	75.3 ^{fghi}	40.6 ^{ijk}	40.8 ^{fgh}	18.7 ^{ij}
		1	77.5 ^{fgh}	66.6 ^{ghij}	68.6 ^{fgh}	46.9 ^{gh}
		2.5	88.8 ^{def}	84.5 ^{defgh}	98.5 ^{cdef}	57.9 ^{efg}

†Means (n = 3) of treatments during the same sampling period follow by the same letter are not different at 5% significant level by Tukey test.

Similar to the oxalate-P data, the effects of the P-sources were not seen in P-based treatments on the soil Total recoverable P values because of similar quantity of P applied (44 kg

ha^{-1}) from the different P-sources. On the other hand, in N-based treatments, Total P values were greatest in Boca Raton biosolids and least in TSP treatments. Thus, comparing the P-sources treatments at N-based rates requires normalizing for differences in the soil P loads. Soil Total recoverable P increased with WTR at the two rates for the different P-sources due to P contained in the WTR. The soil P load was increased by about 50% and more than 100% by the added P from WTR at 1% and 2.5% WTR rates, respectively. The estimated increase in soil P concentrations by the WTR, were 27 mg P kg^{-1} and 67.5 mg P kg^{-1} for 1% and 2.5% WTR treatments, respectively.

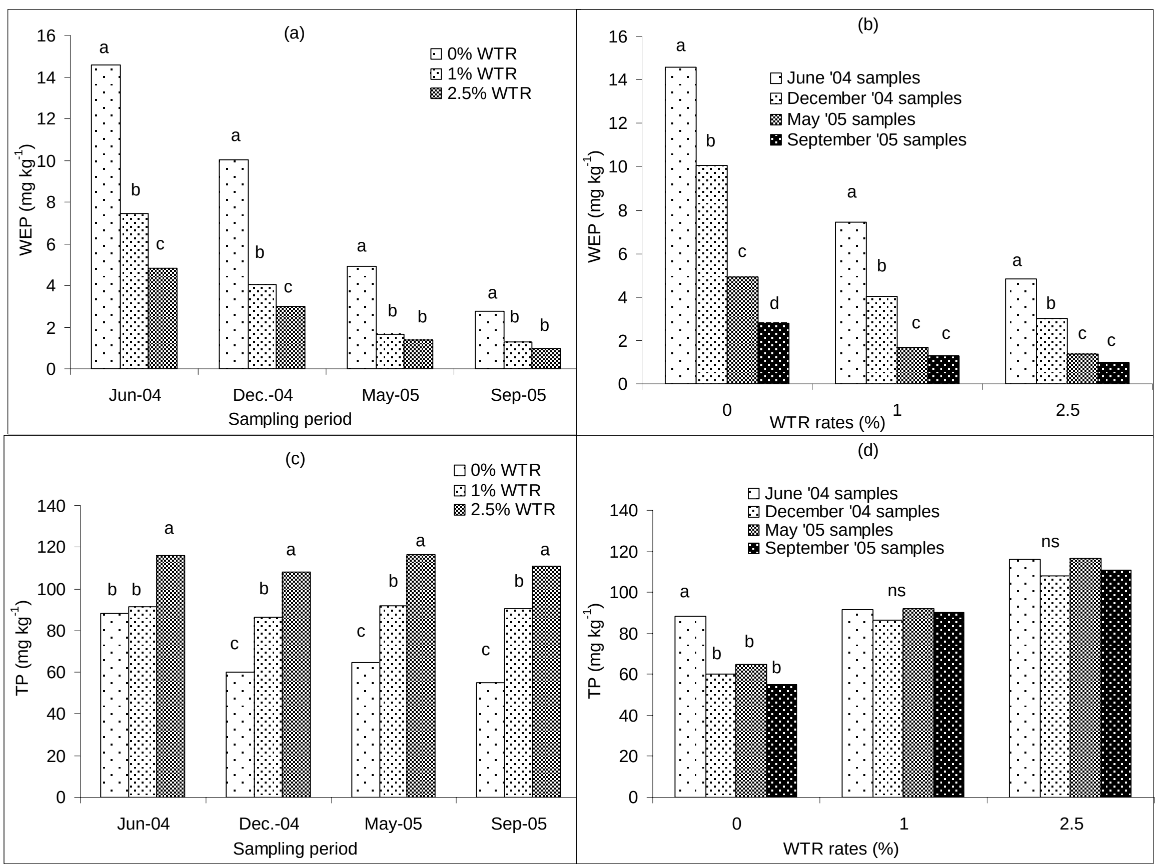


Figure 3-3. Trends of soil water extractable P (WEP) and Total recoverable P (TP) values as affected by time and WTR treatments. (Treatments within the same sampling period in (a) and (c) or within same WTR rate in (b) and (d) with same letter are not different at *p*-value of 0.05 by Tukey test.

The average soil Total recoverable P values in the absence of WTR were reduced between June and December 2004, but stabilized through the end of the study. The reduction could result from greater P uptake by plants in the absence of WTR. However, in the presence of WTR (1% or 2.5%), the average Total recoverable P values were similar for the different sampling periods (Fig. 3-3d). The trend indicates negligible P uptake by plants relative to soil P loads in WTR treated soils, but greater P uptake by the first cropping in soils without WTR treatments. The P uptake in the absence of WTR was twice the P uptake in the presence of WTR at the two P-source rates of almost all P-sources. Another explanation of the variability of time zero soil P values is the inability to achieve thorough mixing even with the efforts of daily mixing during the one week incubation period. This observation was also supported by the June 2004 soil P load data, which were similar for 0% and 1% WTR treatments within the first six months of the study, but lower at 0% WTR than at 1% WTR afterwards (Fig. 3-3c).

The soil soluble P, as measured by soil WEP values, decreased with time in the absence of WTR (Fig. 3-3b). However, in presence of WTR, the WEP values decreased only within the first year (June 2005 to May 2006), and were similar thereafter (between May and September 2005). The effect of increasing WTR rates was also obvious in the first six months, where soil WEP values decreased linearly as WTR increased from 0% to 2.5%. However, in samples taken in May 2005, and afterwards, soil WEP values were similar for the 1% and 2.5% WTR treatments (Fig. 3-3a).

Soil P and Sorption Properties as Affected by WTR

The effects of WTR treatments on soil soluble P values at the two P-source rates during the study are summarized in Fig. 3-4. Both WEP and ISP determinations reflected the sorbing effect of WTR, as both measures of soil P were reduced with increasing WTR rates. The two soil test methods are environmental soil test methods, and ISP has been shown to be a good measure of soil bioavailable P (Sharpley, 1993a, b).

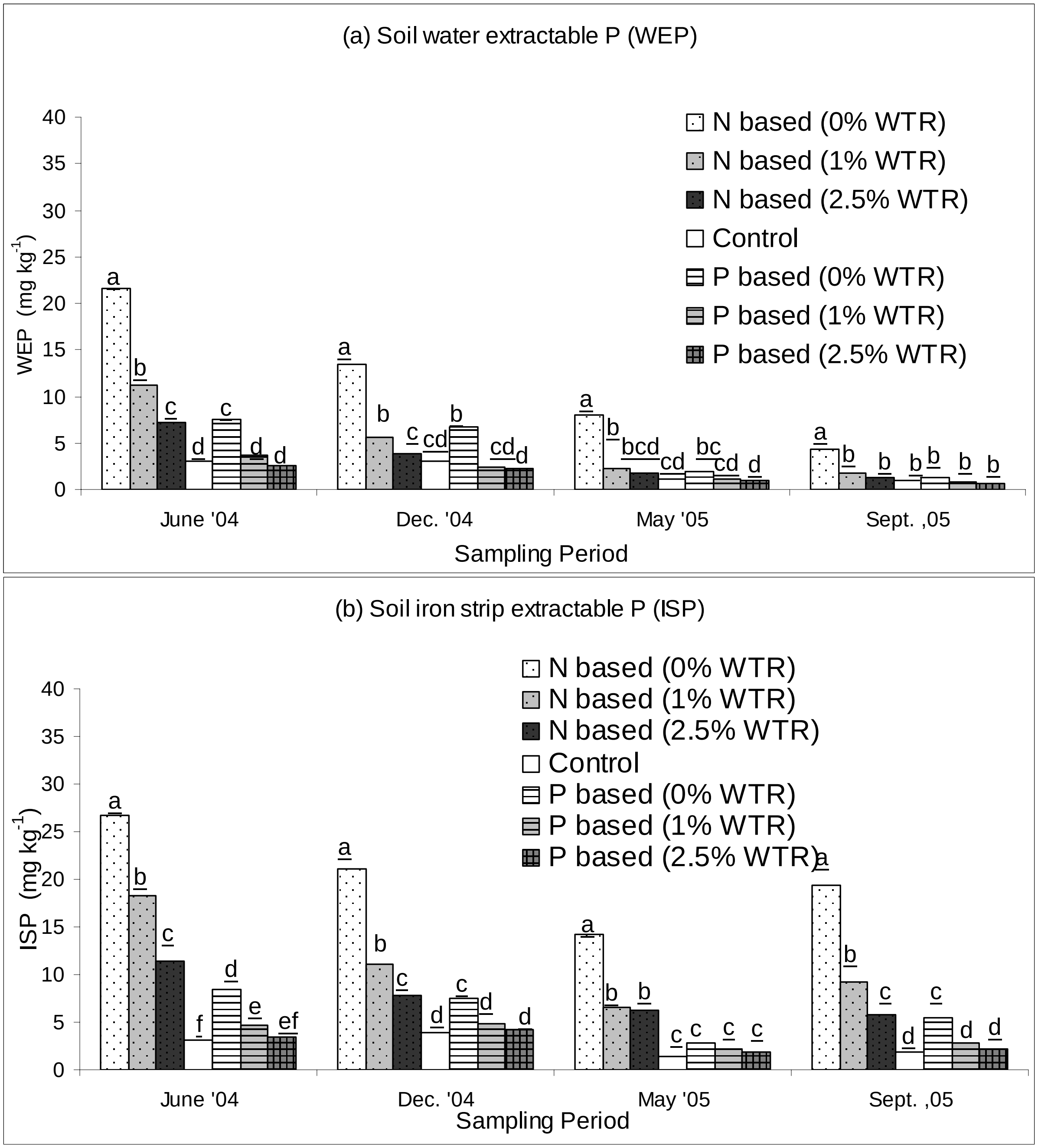


Figure 3-4. Effects of WTR and P-source rates on (a) water extractable P (WEP)and (b) Iron strip extractable P (ISP) values of soil samples taken during the glasshouse study. Treatments within the same sampling period with same letter are not different at *p*-value of 0.05 by Tukey test.

Their reduction with increasing WTR rates established the capability of WTR to reduce soil soluble P and, hence, P loss potential. Within the one week of amendments equilibration, the WEP values of N-based treatments with 2.5% WTR were similar to WEP values of P-based treatments without WTR. Greater ISP values at N-base rates (with 2.5% WTR) than at P-based (without WTR) indicated more readily available P even at 2.5% WTR. Thus, within a week of application, the potential hazards associated with N-based rates could be reduced to that with P-based rates, while maintaining sufficient available P for plants.

Soil M-1P values were either similar at each rate of the P-sources for the three WTR rates or increased with increasing WTR rates (Fig. 3-5a). The acidic extractant (pH<2) apparently solubilizes some of the WTR-sorbed P that will not be available at the soil specific pH, and thus, could not distinguish sorbed P by WTR and the readily available P.

The trend of Total recoverable P values with treatments was similar at each sampling period throughout the study (Fig. 3-5b). The trend was increasing Total recoverable P with WTR at each of the application rate of the P-source. Thus, though soluble P was reduced in presence of WTR, the P was retained in the soil (as shown by the greater soil TP values) and suggests improvements in the P sorption properties of the sandy soil.

Soil total recoverable or oxalate extractable Al and Fe concentrations can indicate sorption characteristics of a soil. The soil Al concentrations were affected by the amounts of WTR applied (Table 3-4). Similar Al concentrations were observed for N-based and P-based rates at each WTR rate throughout the study indicating negligible contributions of the P-sources to the soil Al concentrations. However, soil Al concentration increased with increasing WTR rate. In the absence of WTR, the soil Al concentrations of N-based and P-based rates were similar to the baseline concentrations observed in control. Unlike Al, the soil Total recoverable Fe concentrations were affected by the contributions from both sources of P rate and WTR.

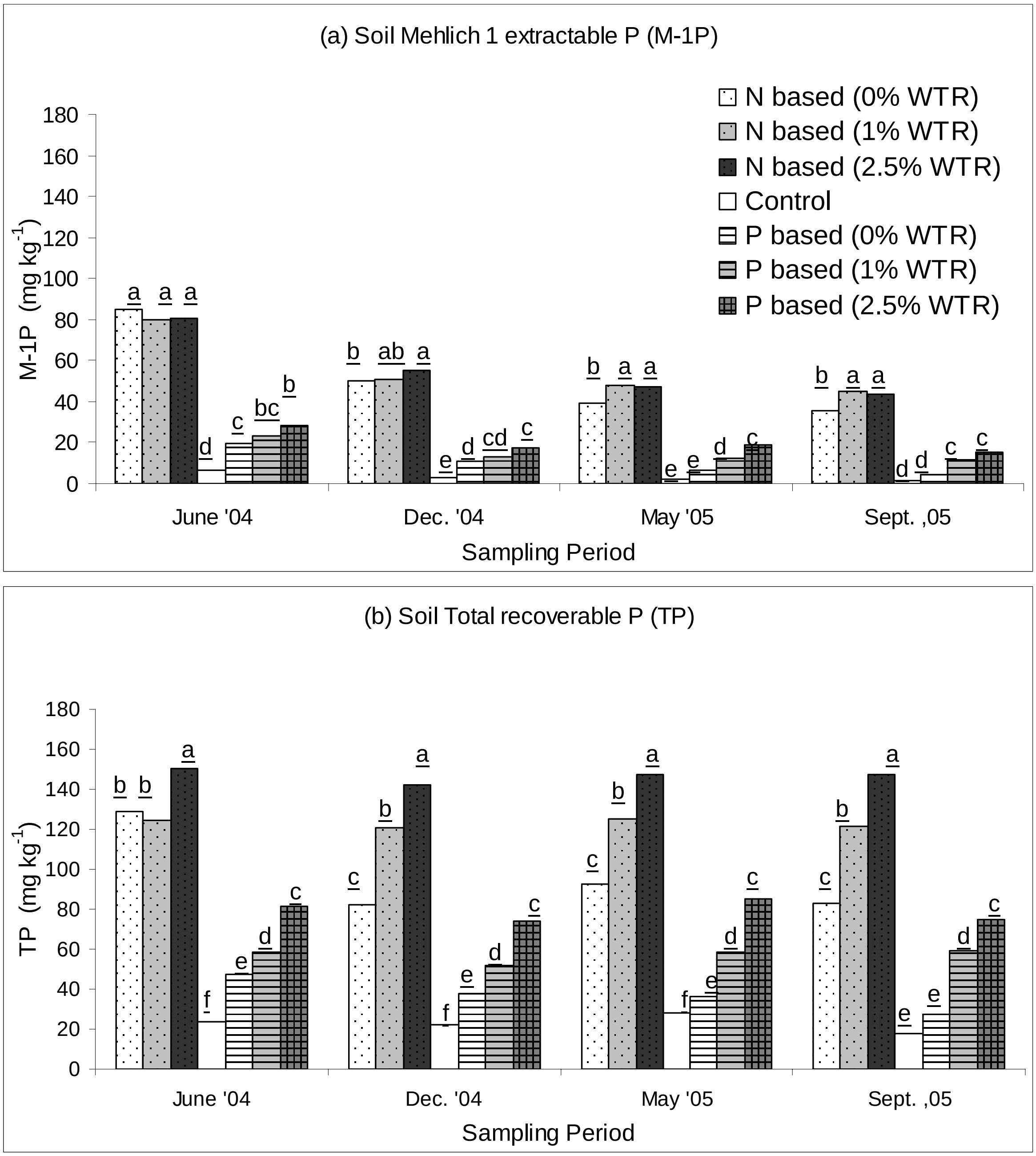


Figure 3-5. Effects of WTR and P-source rates on (a) Mehlich 1P and (b) Total recoverable P values of soil samples taken during the glasshouse study. (Treatments within the same sampling period with same letter are not different at *p*-value of 0.05 by Tukey test.

The greatest Fe concentrations were observed at the N-based rates with 2.5% WTR, while the concentrations at the P-based rate without WTR were similar to the control treatments throughout the study (Table 3-4). Greater Fe (than Al) concentrations in the P-sources could result in the observed greater soil Fe at N-based rates than at P-based rate.

Table 3-4. Soil Total recoverable Al and Fe concentrations as affected by water treatment residual (WTR) and the P-source application rates during the glasshouse study.

P-source rate	WTR (%)	Total recoverable Al ($mg\ kg^{-1}$)				Total recoverable Fe ($mg\ kg^{-1}$)			
		†June '04	Dec. '04	May '05	Sept. '05	June '04	Dec. '04	May '05	Sept. '05
N-based	0	124^{c}	152^{c}	235^{c}	95.7^{c}	136^{cd}	140^{c}	150^{bc}	110^{b}
	1	491^{b}	483^{b}	528^{b}	375^{b}	153^{bc}	154^{bc}	172^{ab}	114^{b}
	2.5	1007^{a}	976^{a}	1072^{a}	850^{a}	184^{a}	187^{a}	199^{a}	143^{a}
P-based	0	107^{c}	86.5^{c}	111^{c}	81.4^{c}	108^{e}	114^{d}	112^{d}	82.6^{c}
	1	427^{b}	404^{b}	511^{b}	425^{b}	133^{d}	140c	130^{cd}	117^{b}
	2.5	956^{a}	1020^{a}	1129^{a}	845^{a}	165^{b}	171^{ab}	169^{ab}	114^{b}
Control	0	88.4^{c}	57.1^{c}	97.0^{c}	68.4^{c}	107^{e}	109^{d}	103^{d}	77.3^{c}

†Means (n = 12) of treatments during the same sampling period follow by the same letter are not different at 5% significant level by Tukey test

The contributions of the soil P, Fe, and Al concentrations to the soil sorption properties could be summarized into indices of soil P sorption, such as Degree of P Saturation (DPS), or Soil P Storage Capacity (SPSC). The DPS, as the name implies, is an index of soil P sorption site saturation and, thus, a measure of capability of the soil to hold and prevent loss of P through runoff and leaching. Large DPS values suggest limited soil capability to retain P. Soil DPS is calculated as the ratio of the soil 0.2M oxalate extractable P to the corresponding 0.2M oxalate Fe and Al and assuming an α value of 0.55 (recommended for Florida soils by Nair et al., 2004).

$$DPS = (P_{ox}) / \alpha\ (Al_{ox} + Fe_{ox}) \qquad \text{(Equation 3-1)}$$

Where P_{ox}, Al_{ox}, and Fe_{ox} are 0.2M Oxalate extractable P, Al, and Fe (expressed in moles), respectively.

The DPS values of all soils that received P application (without WTR), exceeded 25%. Co-applying P-sources at the P-based rates along with 1% WTR and at N-based rates along with 2.5% WTR, resulted in DPS values below the critical value of ~25% (Fig. 3-6). Nair et al. (2004) observed a changed point at 20% DPS, agronomic high M-1P values (30 mg P kg^{-1}) at 22% DPS, and very high M-1P values (60 mg P kg^{-1}) at 28% DPS. The critical M-1P value (50 mg P kg^{-1}, Paulter and Sims, 2000), is equivalent to 25% DPS.

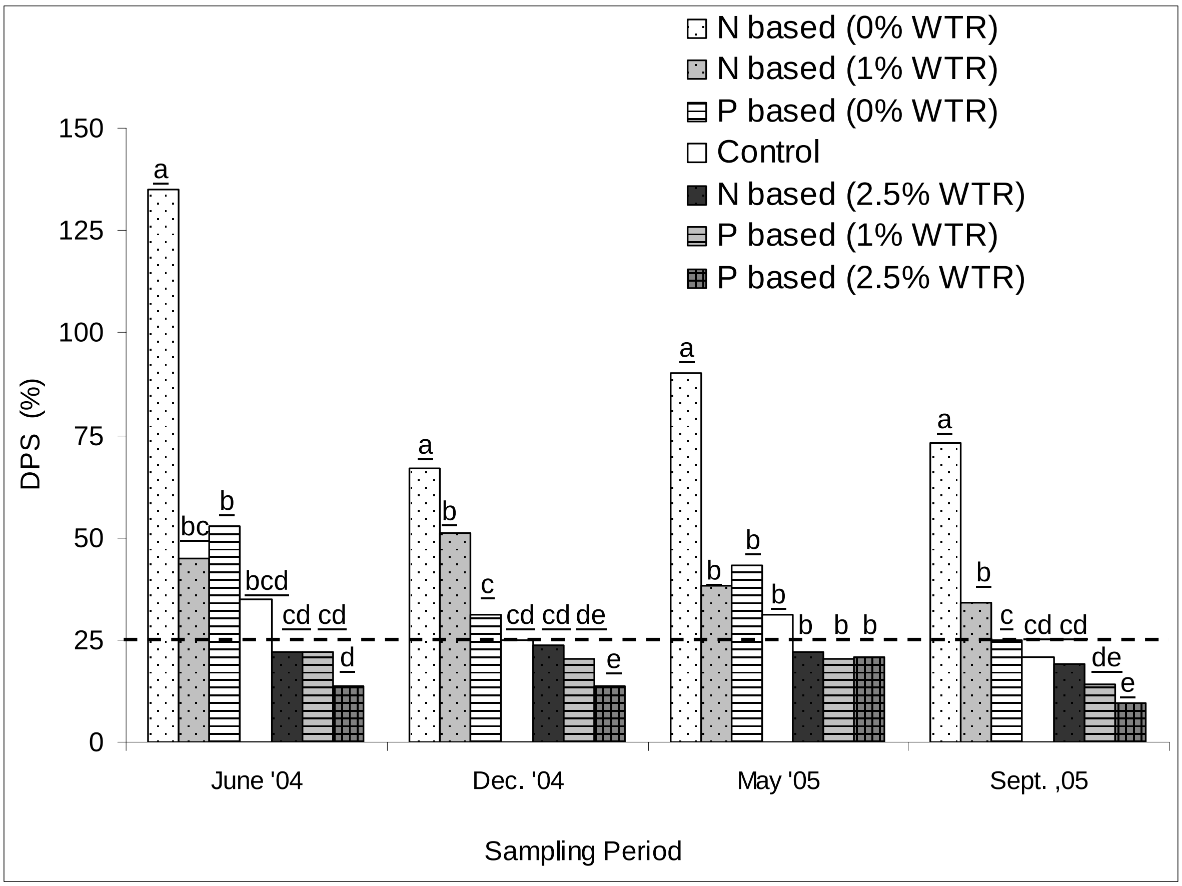


Figure 3-6. Effects of WTR and P-source rates on degree of P saturations (DPS) values of soil samples taken during the glasshouse study. (Treatments within the same sampling period with by the same letter are not different at 5% significant level by Tukey test). Dotted line represents 25% threshold DPS value.

The data show that the P-sorption properties of sandy, low P-sorbing Florida soils could be enhanced with WTR, and that the amount of WTR needed is dictated by the P-source and source application rates. The reduction in DPS values with WTR addition also explains the reduction in soil soluble P with WTR addition.

A plot of WEP values against the DPS values of all the soils sampled during the study shows increasing WEP values with increasing soil DPS (Fig. 3-7). The increased soil sorption sites (indicated by reduced DPS), reduces soil soluble P. The variation of soil DPS values at the same P application rate and WTR rate reflects differences in compositions of P-sources, especially P, Al and Fe concentrations, and suggests the need to account for these variations in determining the rates of WTR to achieve similar soil DPS.

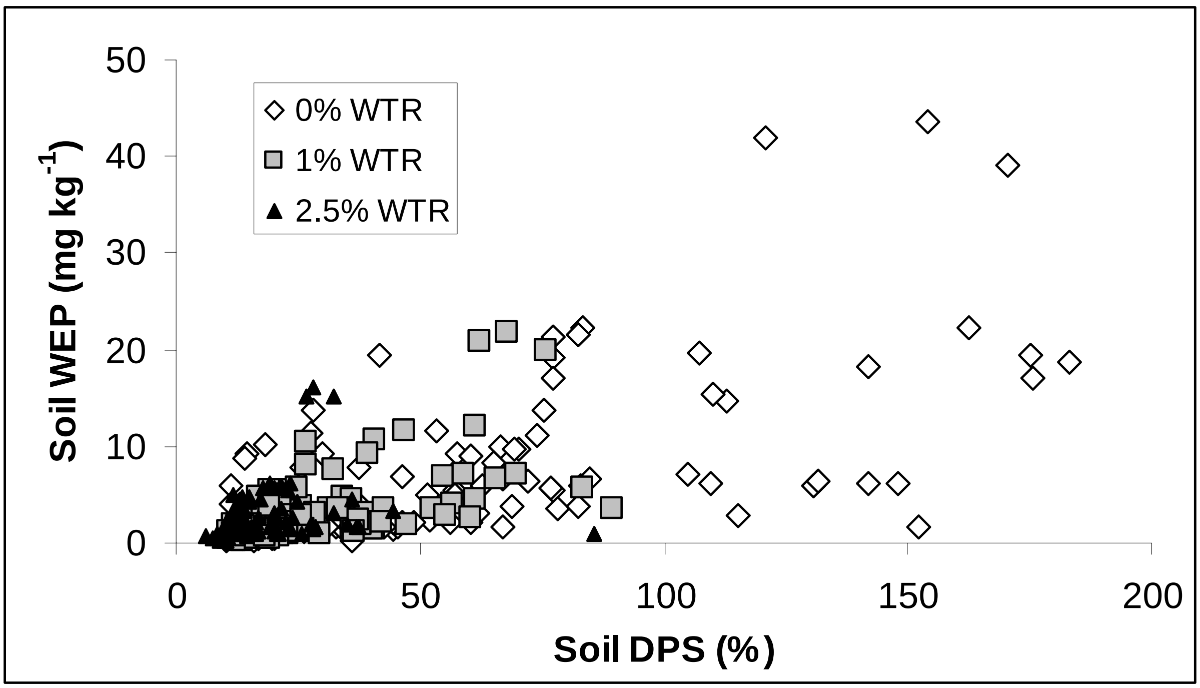


Figure 3-7. The water extractable P (WEP) values as affected by degree of P saturation (DPS) of soil samples taken during the study.

The soil phosphorus storage capacity (SPSC) is another index suggested recently by Nair and Harris (2004) to quantify the amount of P a soil can sorb before exceeding the threshold soil equilibrium P concentration. The SPSC is calculated as:

$$SPSC\ (mg\ P\ kg^{-1}) = (0.15 - PSR)*(Al_{ox} + Fe_{ox})*31 \qquad \text{(Equation 3-2)}$$
$$PSR = P\ saturation\ ratio = (P_{ox})/(Al_{ox} + Fe_{ox}) \qquad \text{(Equation 3-3)}$$
Where P_{ox}, Al_{ox}, and Fe_{ox} are 0.2M Oxalate extractable P, Al, and Fe, respectively.

The 0.15 value used in SPSC calculation corresponds to the critical solution P concentration of 0.10 mg L^{-1} (threshold) proposed by Breeuswsma and Silva (1992). Zero SPSC indicates a soil PSR value of 0.15 and solution P concentrations ≤ 0.10 mg L^{-1}. The greater the SPSC value, the more applied-P a soil can retain (sorb). Generally, SPSC values of time zero soil samples increased with increasing WTR rates (Fig. 3-8) due to added Al. The SPSC was more negative at N-based rates than at P-based rates due to greater added P at N-based rate, which increased saturation of the P sorption sites.

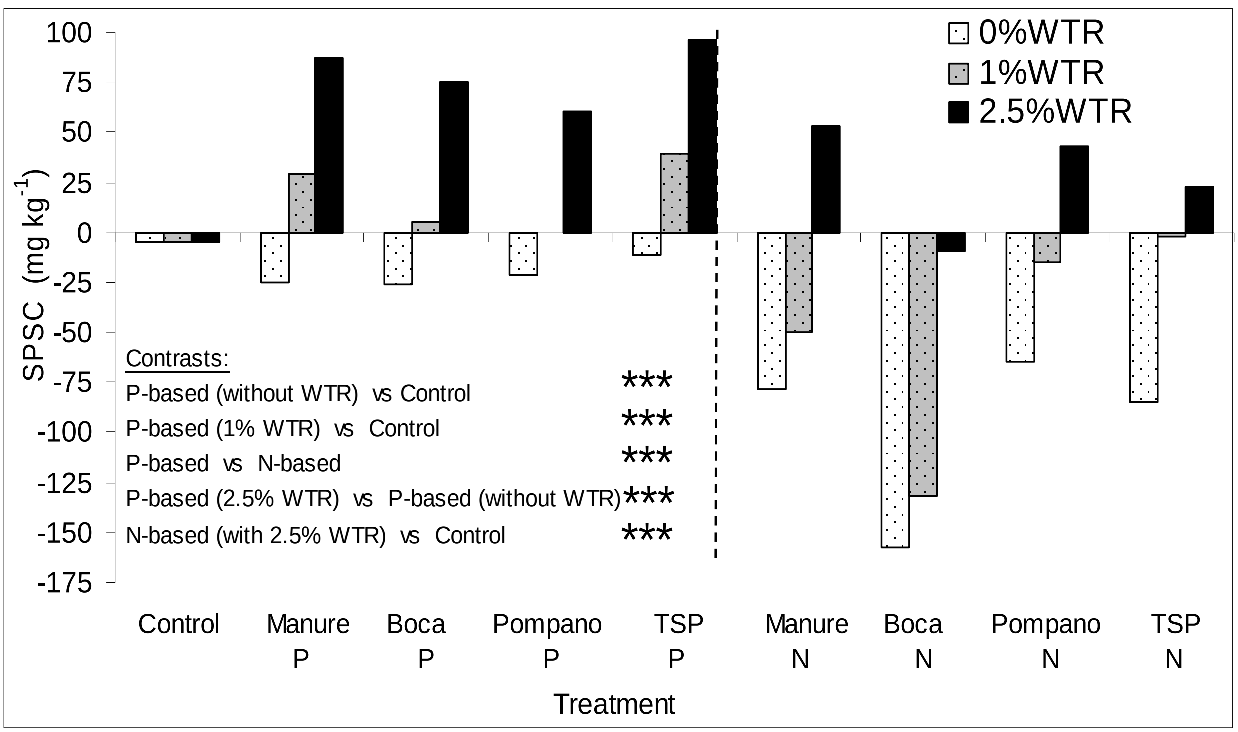


Figure 3-8. Soil phosphorus storage capacity (SPSC, mg kg^{-1}) values of time zero samples taken during the glasshouse study for the different treatments. (Treatments ending in P, and N, are P-based and N-based rates of the sources, respectively).

The SPSC values at the P-based rates of the sources, without WTR, were close to 0 mg P kg^{-1} confirming the P-based rate as environmentally friendly (Fig. 3-8). However, N-based rates without WTR (and even at 1% WTR) resulted in negative SPSC values. The greatest negative SPSC value was observed in Boca Raton biosolids, N-based treatment. Negative values of SPSC indicate that a soil contains excess P, and suggest that N-based rates could cause negative environmental impacts (Reddy et al., 1980; Pierzynski, 1994; Peterson et al., 1994; Maguire et al., 2000). With addition of WTR, the SPSC values of the N-based rates of all P-sources increased and were positive for most P-sources (except Boca Raton biosolids) at 2.5% WTR. Thus, application of WTR creates P sorption sites for soil soluble P in excess of 0.10 mg L^{-1} at the N-based rates. Addition of WTR increases the storage capacity at both the P-based and N-based rate. However, SPSC is greater at P-based than at N-based rates when equal amounts of WTR are applied. Different amounts of WTR will be required to bring soils treated with different P-sources at N-based rates to equal SPSC values.

Plant P Uptake, P Concentrations and Dry Matter Yield

Plant uptake of P was affected by the P-source, P-source rates and WTR rates. The P uptake of each cropping, and the Total P uptake (sum of the uptakes from the three croppings), were greater at the N-based rates than at the P-based rates at each level of WTR (Fig. 3-9). Addition of WTR reduced P uptake at each P-source rate. The P uptake was greater in the absence of WTR than at 1% or 2.5% WTR, and most WTR-sorbed P was not accessible by the plants. However, greater P uptake was observed in ryegrass and in the second bahiagrass crop at N-based rates with 1% and 2.5% WTR than at P-based rates without WTR. The greater P uptake, indicates that applying WTR to N-based rates reduces P uptake, but not below the P requirements of the plants, which is expected to be optimum at P-based rate (with no WTR). We, therefore, fail to reject hypothesis I and II and conclude that P-based rates (without WTR) and N-based rates (with WTR) both result in minimized soil soluble P and optimized plant P uptake.

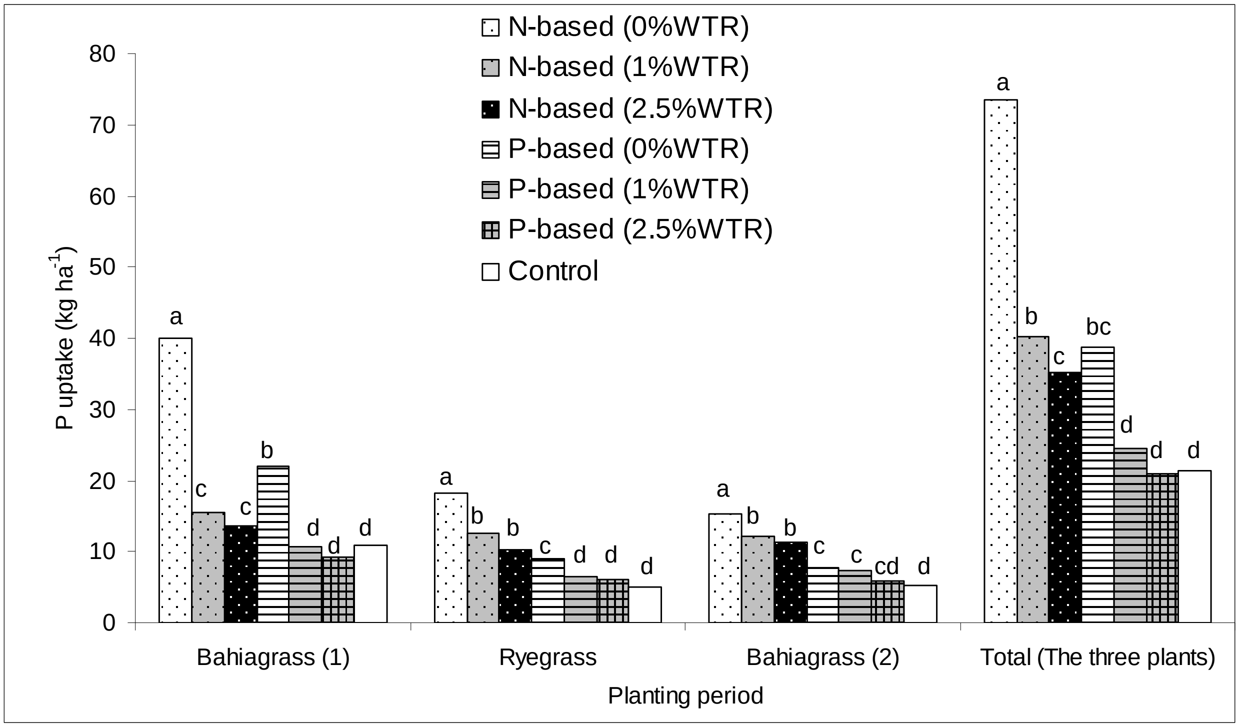


Figure 3-9. Effects of water treatment residual (WTR) and P-source rates on plant P uptake during the glasshouse study. Treatments within the same cropping with the same letter are not different at 5% significant level by Tukey test.

The greater P uptake of the three individual croppings and the total P uptake for the entire growing season at P-based rate without WTR than at the P-based rate in the presence of WTR indicate it is not advisable to apply WTR to P-based rate. In presence of WTR, the uptake of the two bahiagrass croppings and the total P uptake values at the P-based rate were not different from those observed in the control treatment. Similar P uptake was observed for 1 and 2.5% WTR treatments in the three croppings at P-based rate and in the first bahiagrass and ryegrass croppings at N- based rates. Thus, increasing the WTR rates from 1% to 2.5% did not further reduce P uptake.

The trends of the P concentrations of the two bahiagrass croppings were similar to the P uptake data. Plant P concentrations were smaller in the presence, than in the absence, of WTR at each application rate and greater in N- than P-based treatments. Ryegrass P concentrations were also reduced with increasing WTR rate at each P-source rate (Fig. 3-10). The P concentrations at the N-based rate, with WTR, were similar to those at the P-based rate without WTR for ryegrass and even greater at N-based rates with WTR than P-based rates without WTR for the second bahiagrass crop. The similar plant P concentrations suggest that application of WTR, even at 2.5%, will not reduce plant P concentrations below the optimum observed at P-based rate without WTR. Plant P concentrations in the second bahiagrass cropping were greater than in the first cropping in WTR-amended soils, and vice versa in treatments without WTR. The data suggest that P-sorbed by the WTR could be assessed by the plants over time, when plants are in the deficiency stage.

The greater P concentrations of the second bahiagrass crop could also be due to "Steenbjerg effect", where plant nutrient concentrations increase when plants are subjected to nutrient deficiency (Steenbjerg, 1951; Bates, 1971). Nutrient deficiency destroys potential for growth, but plants continue to accumulate the nutrient, resulting in greater nutrient concentrations during deficiency periods (Ulrich and Hills, 1967; Jones, 1967; Bates, 1971).

Though the P concentrations of the grasses were reduced when WTR was applied, the least P concentration observed during the two bahiagrass croppings (1.73 g kg^{-1}) was above the 1.3 g kg^{-1} mean P concentration reported for bahiagrass (USDA, 1996). Also, the least P concentration observed in ryegrass samples (1.82 g kg^{-1}) was above the 1 g kg^{-1} regarded as sufficient for ryegrass (Hylton et al., 1965). The reductions in P concentrations are consistent with other studies that show plants grown in potting media treated with WTR had lower P concentrations (Bugbee and Frink, 1985; Elliott and Singer 1988). Ippolito et al. (1999) also reported decreasing P concentration, but increasing plant yields with increasing WTR rates.

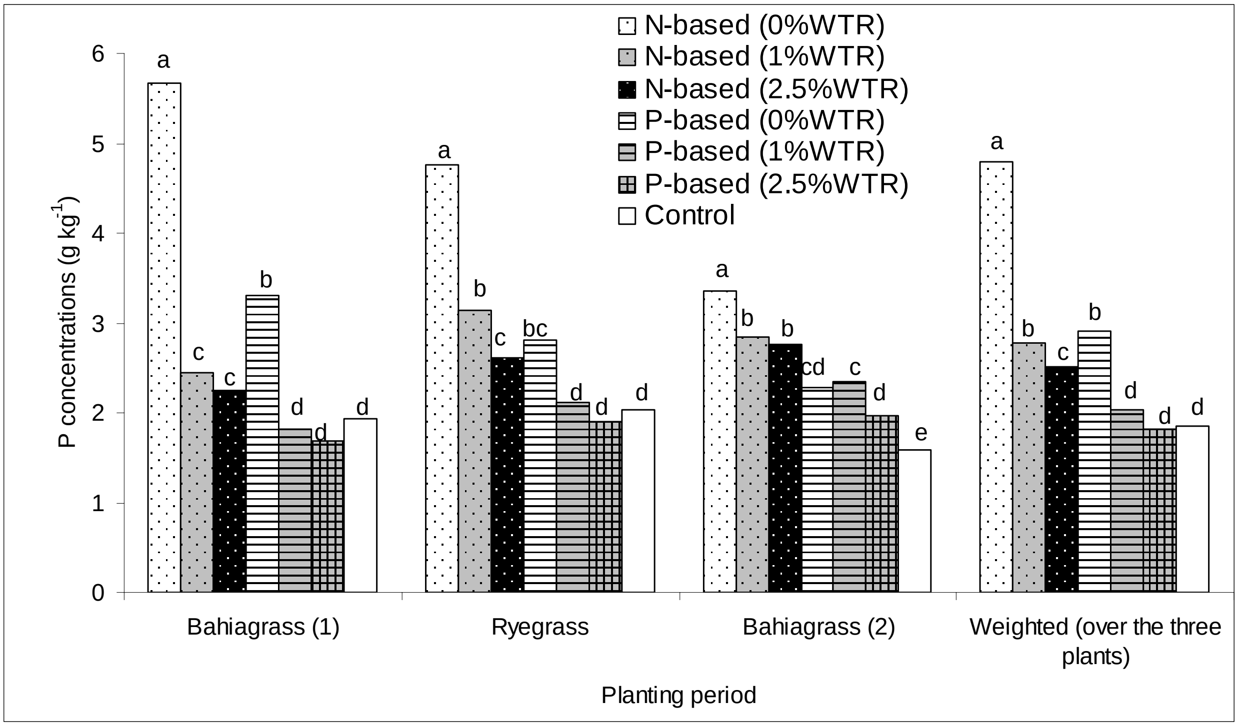


Figure 3-10. Effects of water treatment residual (WTR) rates and P-source rates on plant P concentrations. Treatments within the same planting with the same letter are not different at 5% significant level by Tukey test.

Yield reduction was observed in the first bahiagrass cropping with increasing addition of WTR (Fig. 3-11). Reduced yields may have partly resulted from irregular growth of the grass due to germination difficulties encountered during the grass establishment. However, the yield of the ryegrass and the second bahiagrass croppings at N-based and P-based rates with WTR were similar to the yields of similar treatments in the absence of WTR. Thus, the yields of the plants were not affected even at 2.5% WTR at both N-based and P-based rates.

The yields of the ryegrass and the second bahiagrass croppings were greater at N-based than at P-based rates. The N-based rates not only supplied adequate nutrients, but enhanced yields for longer periods than the P-based rates. Total plant dry matter yields from the three croppings at N-based rates (even with WTR) were greater than yields at P-based rates (in the absence of WTR). However, the greater yields of N-based treatments may be not be economical considering the greater negative P impact of the high P rate on the environment. Thus, P-based rates (without WTR) and N-based rates with WTR optimize plants dry matter (DM) yields.

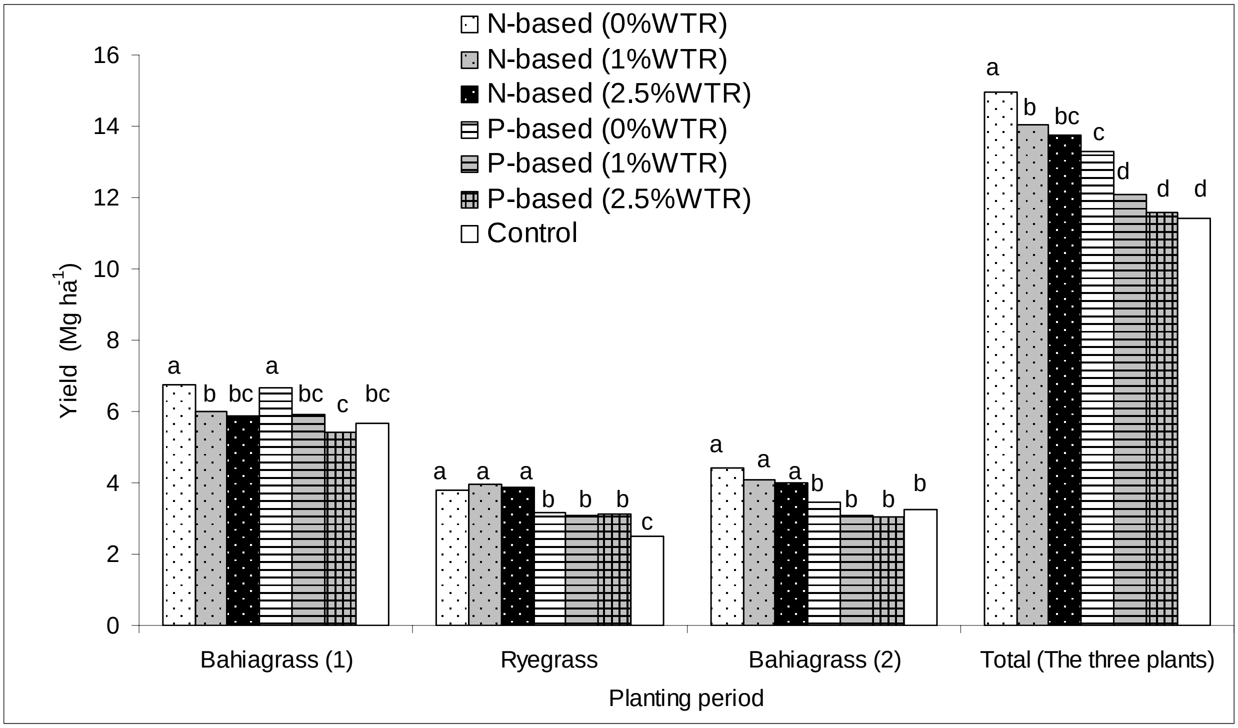


Figure 3-11. Effects of water treatment residual (WTR) and P-source rates on plant dry matter yields. Treatments within the same planting period with the same letter are not different at 5% significant level by Tukey test.

The yields of the plants were also affected by the P-sources (Table 3-5). For the P-based rates (equal P loads), the yields of the two bahiagrass croppings were similar for the different organic source of P, but greater than the yields obtained from TSP treatment. Ryegrass yields from the TSP treatments were similar to yields from organic sources of P treatments. Similarly, at the N-based rates, the yields of ryegrass and the second bahiagrass cropping from organic sources of P treatments were greater than yields from the TSP treatments. The data indicate that organic sources are not inferior to the mineral fertilizer in terms of the agronomic returns (yields). Rather, the organic sources, which act as slow release P fertilizer, promote more efficient utilization of the added P.

Table 3-5. Effects of P-source and source application rates on plant dry matter yields† ($Mg\ ha^{-1}$).

Plant	Source of P / Contrast	Rate: N-based	Rate: P-based	Contrast N-based vs P-based
First Bahiagrass cropping	Manure	4.55†	6.52	*
	Boca Raton biosolids	7.53	5.97	*
	Pompano biosolids	6.65	5.91	*
	TSP	6.11	5.62	*
	Manure vs Biosolids	*	NS	
	Organic vs Mineral source	NS	*	
	Boca Raton vs Pompano	*	NS	
Ryegrass cropping	Manure	4.38	3.36	*
	Boca Raton biosolids	4.06	2.95	*
	Pompano biosolids	3.75	3.06	*
	TSP	3.30	3.14	NS
	Manure vs Biosolids	NS	*	
	Organic vs Mineral source	*	NS	
	Boca Raton vs Pompano	*	NS	
Second Bahiagrass cropping	Manure	3.99	3.17	*
	Boca Raton biosolids	5.54	3.23	*
	Pompano biosolids	4.28	3.39	*
	TSP	2.83	2.97	NS
	Manure vs Biosolids	*	NS	
	Organic vs Mineral source	*	*	
	Boca Raton vs Pompano	NS	NS	

† Means of nine samples
* Significant at P = 0.05%
NS not significant at P = 0.05%

The yields of first the bahiagrass cropping were greater at N-based rates than at P-based rates, except for soils amended with manure at the N-based rate. The N-based manure treatment took extra time to establish thus resulted in the lower yields observed at N-based than P-based rates (Table 3-5). The greater pH of soils treated with manure at N-based rates (pH>7) than the targeted pH (5.5) also likely reduced bahiagrass yields for the N-based treatment. Lower yields of bahiagrass at high, than at low, rates of manure were also reported by O'Connor et al. (2005). The yields reported at low P rate were twice the yield at a high P rate, and were also attributed to a greater soil pH at high P rate than the so called target pH for bahiagrass (pH = 5.5). Ryegrass and second bahiagrass croppings yields, were greater at N-based than P-based rate of the sources, except in TSP treated soil where similar yields, were observed for the two rates. The similar yields of P-based rates of TSP to that observed at high P-rate established that the P-based rate optimized plant yields and can serve as the basis for comparing the yields from other treatments.

The relative agronomic yield (RAY) term was obtained for each croppings by relating the yield obtained from each treatment to the greatest yield, and expressed as percentage (Table 3-6). The TSP treatments did not give the greatest RAY for the three croppings (individually or collectively). However, the P-based TSP treatment could still serve as basis for comparison of the agronomic benefits, as it proportionately represents sufficient readily available P and N for optimal plant growth.

The RAY values of treatments with WTR are either greater than or similar to RAY values of the P-based rate of TSP without WTR. This indicates no reduction in yield below the optimum expected when WTR is co-applied with organic source of P at either of the two P-source rates. Possible reductions in yield were indicated by lower RAY values in some WTR-amended treatments than in non-WTR treatments for P-based rate. The smaller RAY values obtained in manure treatments at N-based rate of the first bahiagrass cropping (<77%) may be connected with greater soil pH values (> 7) in manure treatments which are not favorable for growth of the acidic soil loving bahiagrass as earlier explained. The same manure treatment resulted in the greatest RAY values for ryegrass, which is more tolerant to high soil pH.

Table 3-6. Relative agronomic yield (RAY) values of the different treatments (%)

P-source	Rate	WTR (%)	Bahiagrass (1)	Ryegrass	Bahiagrass (2)	Combined†
Control	-	-	69	55	58	65
Manure	P-based	0	87	75	58	79
		1	78	75	57	74
		2.5	74	74	53	71
	N-based	0	63	100	68	77
		1	54	98	76	75
		2.5	50	94	68	69
Boca Raton biosolids	P-based	0	83	69	64	77
		1	70	63	57	67
		2.5	66	65	52	64
	N-based	0	100	85	98	100
		1	91	92	96	97
		2.5	86	94	100	96
Pompano biosolids	P-based	0	80	70	62	75
		1	71	68	55	68
		2.5	66	65	62	68
	N-based	0	84	81	85	87
		1	80	85	74	83
		2.5	80	84	68	81
TSP	P-based	0	77	68	61	73
		1	71	68	50	66
		2.5	59	74	47	61
	N-based	0	83	73	60	77
		1	69	76	44	66
		2.5	72	72	46	67

† RAY based on sum of DM yields for the three croppings

The combined RAY values were based on total DM yields obtained from all three croppings, and trends in RAY values agreed with the trends for individual cropping. The data suggest that both P-based and N-based rates of different P-sources together with WTR optimized agronomic yields. Also, a P-based rate of poultry manure is advised if bahiagrass is to be grown. An N-based rate of the Ca-rich poultry manure will result in greater soil pH than tolerated by bahiagrass and will reduce the yield.

Relative Phosphorus Phytoavailability (RPP)

Relating extractable P to the ability of organic sources to supply plants with P has not been successful (Beegle, 2005, Elliott et al., 2005). The P-release characteristics of biosolids were compared to plant P uptakes by McLaughlin (1988). The potential for P release to plants was not only underestimated by the extractants, but the time P-release characteristics were also poorly predicted.

The relative P phytoavailability (RPP) is a comparative measure of the availability of phosphorus from P-sources to plants. Other studies used regression parameters to calculate the RPP (McLaughlin and Champion, 1987; O'Connor et al., 2004). However, both regression methods and point estimates were used in this study, and treatments without WTR were used.

To study how RPP is affected by the plants, P-sources, and P-source rates, point estimates of the RPP were calculated for each experimental unit. The point estimate is appropriate for treatments where all plant nutrients are adequate and treatments have equal soil P loads. Both N- and P-based rates (without WTR) satisfy the condition of adequate nutrients. However, the assumption of equal soil P loads is satisfied only by the P-based rates for the first bahiagrass croppings and the subsequent croppings (if P-applied is adjusted for P uptake by previous crop). The N-based rates also can be normalized to satisfy the condition of equal P loads if expressed as P uptake per unit P load. Thus, the use of P uptake per unit P load will account for the differences in the soil P loads from the different P-sources at N-based rates. The P uptake per unit P load obtained from each P-source is then related to similar ratio obtained for TSP to arrive at the RPP expressed in percentage for each source as in Equation 3-4.

$$RPP = \frac{(\text{P uptake}_{source}/\text{P applied}_{source})}{P\ uptake_{TSP}/\ P\ applied_{TSP}} * 100 \qquad \textit{(Equation 3-4)}$$

The TSP treatment served as the basis for comparison with other P-sources because the mineral source of P was expected to give optimum agronomic performance. Fertilizer-P is readily available P and other needed nutrients were adequately supplied for optimum growth. Analysis of variance (ANOVA) indicated P-source, P-source rate and plant cropped affects RPP. The RPP values obtained at each cropping and at P- and N-based rates by point estimate are shown in Table 3-7. The point estimates indicate that RPP values can be affected by the source application rates. At P-based rates, the RPP values were similar for all the P-sources especially for the ryegrass and second bahiagrass croppings, indicating that the plants were as efficient at taking up P from organic sources as from the mineral P-source.

Table 3-7. Relative P phytoavailability (RPP) values for the different P-sources at each P-source rate by point estimate. All RPP values are expressed in %.

Source rate	P-source	Bahiagrass (1)	Ryegrass	Bahiagrass (2)	[†]Average
N-based	Manure	22 [c]	55 [b]	36 [b]	38 [c]
	Boca Raton biosolids	70 [b]	58 [b]	75 [a]	67 [b]
	Pompano biosolids	42 [c]	66 [b]	73 [a]	60 [b]
	TSP	100 [a]	100 [a]	100 [a]	100 [a]
P-based	Manure	94 [ab]	107 [a]	124 [a]	109 [ab]
	Boca Raton biosolids	116 [a]	111[a]	123 [a]	117 [a]
	Pompano biosolids	79 [b]	91[a]	100 [a]	90 [b]
	TSP	100 [ab]	100 [a]	100 [a]	100 [ab]

[†] Average of RPP of the three croppings.
[‡]Means (n = 3) of treatments during the same cropping and at the same P-source rate follow by the same letter are not different at 5% significant level by Tukey test

The RPP of all the P-sources at the P-based rates were, therefore, >75% and categorize all P-sources into high RPP. At the N-based rate, the RPP values obtained by point estimate were ≤ 75%. The RPP values of manure and Pompano biosolids are similar at planting of first bahiagrass and ryegrass but greater for Pompano biosolids than for manure at planting of the second bahiagrass crop. The RPP of manure was greater at cropping of rygrass than at either of the two bahiagrass croppings. The reduced RPP of manure during bahiagrass croppings reflect the low tolerance of the grass to high pH associated with manure treatment. Thus, apart from the impacts of P-source composition suggested from other studies (McLaughlin and Champion, 1987; O'Connor et al., 2004), plant tolerance to pH could also affect the RPP (as observed in manure treated soils). Few effects of most biosolids on soil pH are expected, and plant tolerance to pH may not be an issue as regards RPP of biosolids. However, there may be some special cases, as in Tarpon Spring N-viro biosolids (pH = 11.9) used in a study by O'Connor et al., (2000), which also reduced bahiagrass growth and its RPP.

The regression slope-ratio procedure can define RPP values better than point estimates as it integrates impacts of both source and P rates to the RPP values. The slope-ratio procedure is also widely used to determine P bioavailability (McLaughlin and Champion, 1987; Cromwell, 2002; O'Connor et al., 2004) and, hence will enhance comparison of the results. To obtain the regression RPP estimates, the P uptake from each cropping and the total P uptake for the three croppings were regressed with applied P at 0-rate (control), P-based rates, and N-based rates (adjusted for P uptake of previous croppings).The regression slopes obtained for each P-source were compared with the slope of TSP treatment (the greatest slope) and expressed as percentage as in Equation 3-5.

$$RPP = [(Slope_{source}) / (Slope_{TSP})] * 100 \qquad \text{(Equation 3-5)}$$

The RPP obtained for each P-source by the slope-ratio is shown on Table 3-8. The RPP values obtained (30-100%) were within the ranges from other studies (McLaughlin and Champion, 1987; O'Connor et al., 2004; Pritchard, 2005). The ranges of RPP values obtained by combining the three croppings P uptake and by using uptake from each individual cropping are 30-55% for manure, 68-82% for Boca Raton biosolids and 41-58% for Pompano biosolids. The

RPP values of Boca Raton biosolids for the two bahiagrass croppings (82%) were within the range of "high" phytoavailability materials identified by O'Connor et al. (2004). The reduced RPP value for ryegrass may be due to the crop rather than the source P-lability. The "high rate activated sludge" process by which the Boca Raton material is produced apparently allows similar P availability (indicated by its high WEP) as in biological P removal (BPR) processes.

Table 3-8. Relative P phytoavailability (RPP) values for the different P-sources by regression.

Cropping	Regression parameter / RPP	Manure	Boca Raton biosolids	Pompano biosolids	TSP
First Bahiagrass	Slope	0.076	0.209	0.105	0.256
	r^2	0.71	0.99	0.92	0.99
	p-value	0.16	<0.01	0.04	<0.01
	RPP (%)	30	82	41	100
Ryegrass	Slope	0.068	0.083	0.068	0.123
	r^2	0.94	0.97	0.96	0.99
	p-value	0.03	0.01	0.02	<0.01
	RPP (%)	55	68	55	100
Second Bahiagrass	Slope	0.042	0.095	0.067	0.116
	r^2	0.74	0.98	0.94	0.98
	p-value	0.14	0.01	0.02	0.01
	RPP (%)	36	82	58	100
†Combined	Slope	0.178	0.345	0.223	0.419
	r^2	0.83	0.99	0.95	0.99
	p-value	0.08	<0.01	0.03	<0.01
	RPP (%)	43	82	53	100
RPP Category		Moderate (25-75%)	High (>75%)	Moderate (25-75%)	-

† RPP based on sum of P uptake from the three croppings

The RPP value of Pompano biosolids (41-58%) is similar to biosolids categorized as "moderate" phytoavailability and is characteristic of the RPP values of most conventionally processed biosolids. The available P of some manures has been reported to be about equal to fertilizer-P (Agronomy Guide, 2002), but availability depends on the type of manure and plant grown. The lower RPP value obtained for manure in this study mainly results from high soil pH values (pH > 7.0) associated with the high poultry manure application rates and reduced growth of the acid-tolerant bahiagrass. The reduced growth of bahiagrass at high rate of manure resulted in poor regression and reflected in lower RPP in bahiagrass than in ryegrass. The RPP values of the manure treatments were greater for ryegrass (55%), which is more tolerant of basic soil pH values than for bahiagrass (30 -36%) while Boca Raton biosolids shows the opposite. The reduced RPP of Boca Raton biosolids for ryegrass cropping may also reflect tolerance of the grass to some of the biosolids properties. However, this study is not sufficient to make a more definite reason or conclusion about reasons for the observed trend. The RPP values obtained from manure treatments by individual or combined croppings categorize the amendments into medium RPP. The combined data (based on sum of uptake from the three croppings) gave RPP values similar to those obtained from the individual croppings and categorized manure and Pompano biosolids into the moderate RPP category and Boca Raton biosolids into high RPP category. Thus the residual effect indicated RPP of organic sources did not change with time in Florida sand. The RPP values obtained at first bahiagrass cropping (short term) is similar to values got from the cumulative data and suggested adequacy of the short time studies to evaluate P phytoavailability from organic source.

Aluminum Toxicity

The impact of the applied Al-WTR on Al concentrations of the plants and the potential for Al toxicity was studied using TSP treatments at N-based rates. The applied Al-WTR did not affect plant Al concentrations in any cropping. Plant Al concentrations in treatments that received no WTR were similar to those where WTR was applied, even at 25 g WTR kg^{-1} (Table 3-9). The plant Al concentrations (21 – 80 mg kg^{-1}) are within the range of common (non toxic) plant Al concentrations (10 – 1000 mg kg^{-1}) reported by Pais and Jones (1997) and the average concentration of 73 mg kg^{-1} reported in other studies for bahiagrass (USDA, 1996; Arthington, 2002; Arthington et al., 2002). The phytotoxic species (Al^{3+}) is expected in soil solution with pH ≤ 4.0 (Kennedy and Cooke, 1982). Thus, at the observed soil pH of > 5.2, the less toxic Al species ($Al(OH)^{2+}$, $Al(OH)_2^{+}$, $Al(OH)_3$) predominate in the WTR amended soils. The soil solution Al^{3+}concentration is not expected to exceed 50 µg L^{-1} at pH > 5.2 (Kennedy and Cooke, 1982). This concentration is ten times lower than the 0.5 mg L^{-1} expected to cause toxicity problems with plant root (Sartain, 2005). In addition, complexation of Al with organic compounds from the organic sources of P could further reduce the free Al^{3+}.

Table 3-9. Effect of aluminum water treatment residual (Al-WTR) on bahiagrass (first and second croppings) and ryegrass Al, Ca, and Mg concentrations.

Plant	WTR rate (%) / Contrast	Al (mg kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})
First Bahiagrass	0	59.2	5.94	4.42
	1	66.8	4.97	3.76
	2.5	80.4	5.78	4.18
	Linear	NS	NS	NS
	Quadratic	NS	NS	*
Ryegrass	0	60.8	4.28	4.51
	1	45.6	4.82	4.48
	2.5	51.5	4.92	4.30
	Linear	NS	*	NS
	Quadratic	NS	NS	NS
Second Bahiagrass	0	23.3	2.04	4.05
	1	21.9	1.99	4.28
	2.5	25.8	2.33	4.42
	Linear	NS	NS	NS
	Quadratic	NS	NS	NS
†Average Concentrations of South FL Bahiagrass		‡73	4.30	3.30

*Significant polynomial effect of WTR at *p*-value of 5%.
NSNon-significant polynomial effect of WTR at *p*-value of 5%.
†Arthington, 2002.
‡USDA, 1996.

The lack of Al toxicity is further established by the similar and adequate plant Ca and Mg concentrations measured (Table 3-9). The antagonistic effects of increased Al uptake are expected to reduce the concentrations of other cations especially Ca in the plants. In addition, and most importantly, no symptoms of Al toxicity were observed in any treatment throughout the study. The plant growth was good, and the well-developed roots indicated no Al toxicity. The plant mineral concentrations are also similar to concentrations reported in other studies (Hylton et al., 1965; Arthington, 2002).

Summary and Conclusions

Land application of Al-WTR has potential as a BMP to reduce the environmental hazard associated with excess soil P, without negative agronomic impacts. The P-sources, source application rates, and WTR affected varying measures of soil P values (WEP, ISP, M-1P, TP and Ox-P). Within a short time of application of WTR, the DPS and SPSC values of low P-sorbing sandy soil were improved and soil soluble P was reduced. Applying WTR, even at 2.5%, to N-based rates treatments did not reduce plant yields in most cases. However, at P-based rates, WTR rate >1% reduced yields. Plant P concentrations were reduced by application of WTR, but the P concentrations remained greater than the 1 g kg^{-1}, reported to be sufficient for ryegrass, and the 1.3 g kg^{-1} reported for bahiagrass, even in treatments that received 2.5% WTR at P-based source rates. The Al concentrations of the plants were not affected by the added WTR, and other mineral concentrations were within normal ranges.

The potential environmental hazard associated with excess P-loads from N-based addition of P-sources can be reduced with application of WTR without negative agronomic impacts. As much as 2.5% WTR can be applied to N-based rates treatments, but less than 1% WTR is advised if the need arises to apply the amendment at P-based rates. An alternative to WTR addition is to apply lower water soluble-P materials such as Pompano biosolids, at N-based rates.

The organic sources of P varied in relative P phytoavailability (RPP) values especially at high (N-based) P rates, with Boca Raton biosolids being as readily available as mineral P-sources. Lower RPP values were observed in manure treatments due to the greater soil pH associated with its application, especially at N-based amendment rates. Apart from the properties of the sources known to affect the P-solubility, source application rates, the plant grown (especially plant tolerance to resulting soil conditions after treatments) could affect the RPP.

CHAPTER 4
FIELD VALIDATION OF AGRONOMIC IMPACTS OF LAND APPLIED WTR AND DIFFERENT P-SOURCES

Introduction

Off-site P movement in coastal plain soils is facilitated by the low P binding characteristics of the soils (Harris et al., 1996; Hansen et al., 2002). Applied P readily saturates the sorption capacity of such soils, and P is often lost into nearby sensitive water bodies. One method being suggested to reduce P losses from such soils is the application of chemical amendments to improve P sorption and retention by the soils. Laboratory and rainfall simulation studies have demonstrated the ability of water treatment residuals (WTR) to reduce soil soluble P in Florida soils (O'Connor et al., 2002a; Elliott et al., 2002b; Elliott et al., 2005). A glasshouse study using Florida surface soil confirmed that co-applying WTR with different P-sources could reduce excess soil soluble P while optimizing plant growth and P uptake (Chapter 3). Thus, co-applying WTR with P-sources should reduce edge-of-field P losses without negative agronomic impacts.

Uncertainties about Al phytotoxicity of the Al rich residuals make land application of WTR unattractive to some (Anderson et al., 1995). However, Peters and Basta (1996) used drinking water treatment alum hydrosolids to reduce bioavailable P in soils with no increase in extractable Al after application. Results from the glasshouse study described in Chapter 3 also indicated no negative impacts of the Al-WTR on plants Al concentrations, but the data need to be validated in the field.

Another concern with the land application of organic sources of P is the extent of availability of source-P for plant uptake. Comparative studies indicated that biosolids-P availability to plants can vary from <10% to 100%, relative to TSP, and depended on the method of biosolids preparation, which changed biosolids chemical properties (O'Connor et al., 2004).

The glasshouse study (Chapter 3) also identified differences in relative P phytoavailability of two biosolids, and poultry manure. The inferences from glasshouse studies need to be validated in field settings, as environmental factors (edaphic and climatic) can modify nutrient concentrations in plants (Bates, 1971).

Thus, to ensure consistent and accurate amendment utilization decisions, data from a field study were used to validate the agronomic impacts of the same P-sources and WTR noted in the glasshouse study. It was hypothesized that:

1. Both P-based rates of different organic sources of P (without WTR) and N-based rates (with WTR) optimize plant P uptake in the field as observed in the glasshouse study.

2. Amendment rates (P-sources and WTR rates) selected in (1) that optimize P uptake also minimize soil soluble P in the field.

3. Organic sources of P vary in P phytoavailability in a field setting

4. Land application of Al-WTR will not induce greater plant Al concentrations than unamended soils.

The main objective of the field study was to validate the agronomic impacts of the P-sources and WTR in a real world setting.

Materials and Methods

Experimental Procedure

The field experiment, sponsored by South Florida Water Management District in cooperation with a private company and UF-IFAS, was at Kirton Ranch near Okeechobee, FL. The study site is a ranch dominated by improved pastures, and is located on the eastern border of Okeechobee County, eleven kilometers northeast of Okeechobee, north of the Lake Okeechobee.

Soil at the field site is Immokalee fine sand, a typical Spodosol, classified in the Arenic Alaquods taxonomic group, with distinct A, E, and Bh horizons.

The experiment was a 4X2X2 factorial, with one control in randomized complete block design and 3 replicates. Control received neither P-source nor WTR treatments. The 51 plots (20.7m x 95m each) were arranged in three blocks of 17 plots each. The factors were: four P-sources (Boca Raton biosolids, Pompano biosolids, poultry manure and TSP), two application rates of each P-source (N-based, 179 kg N ha^{-1} and P-based, 39.6 kg P ha^{-1}), and two application rates of WTR (0 and 1% oven dry basis). Thus, the treatments were the same four P-sources, at two application rates each, as in the glasshouse study, but two (rather than three) rates of WTR were tested and treatments were surface applied (rather than incoporated throughout the rooting zone). A maximum of 1% WTR application rate was tested in the field due to limited availability of the material. The test plant was established bahiagrass (*paspalum notatum* Fluggae). Dry matter yields and P concentrations were determined for each of the 2 growing years (2003 and 2004).

The P-source application rates of 39.6 kg P ha^{-1} (equivalent to 80 lbs P_2O_5 $acre^{-1}$) and 179 kg PAN ha^{-1} (equivalent to 160 lbs N $acre^{-1}$) were based on the IFAS recommended rates for bahiagrass hay (Kidder et al., 2002). The TSP fertilizer N-based rate used to mimic N-based amendment applications was 128 kg P ha^{-1} (260 lbs P_2O_5 $acre^{-1}$). The value represented the average rate of P applied when biosolids or manure are applied at N-based rates. Based on the analysis of the materials at time of application, the N-based application rates supplied 175 kg P ha^{-1} (357 lbs P_2O_5 $acre^{-1}$) in Boca Raton biosolids treatments, 123 kg P ha^{-1} (251 lbs P_2O_5 $acre^{-1}$) in Pompano biosolids treatments, and 81 kg P ha^{-1} (166 lbs P_2O_5 $acre^{-1}$) in poultry manure treatments. Ammonium nitrate was applied to the plots that received P-based rates of the organic sources and TSP plots, to equal the N supplied in treatments at N-based rates of the organic sources, and to isolate P as the critical plant nutrient. The nitrogen fertilizer was split applied (22.7 kg per plot (50 lbs per plot) at the start of the experiment and the remainder after the first harvest (2 months later). The amendments were applied only once during the study (May 2003), even though the study extended through December 2004. The Al-WTR (1 % by weight) was applied first, on May 9-13, 2003. The two biosolids and manure were applied from May 13-14, 2003, while the TSP fertilizer was applied on May 19, 2003.

Soil Samplings and Analysis

Soil samples were taken to characterize the site before treatment application in May 2003. The established pasture (bahiagrass) was mowed, but the hay was not removed before amendments were surface applied. Amendments and initial soil samples were analyzed as explained in Chapter 2. Three soil samples per plot from A (0-5cm), E (~ 20-30 cm from the top) and the first 10 cm of the Bh horizon horizons were taken in June 2003 (1 month), January 2004 (8 months), and December 2004 (19 months) after treatment application. Additional soil samples were taken from the A-horizon (0-15cm) in March and December 2004 to determine the impacts of the surface applied treatments on P chemistry throughout the A horizon. Four hurricanes (Charley, Frances, Ivan and Jeanne) impacted Florida within 44 days (August 15 and September 25) in 2004.

All soil samples taken during the field study were analyzed for pH and EC (1:2 solid:solution), total recoverable P, Al, and Fe (USEPA, 1986) and 0.2M oxalate extractable P, Al, and Fe (Schoumans, 2000). Other parameters measured included Mehlich-1 P, WEP, and ISP. All analyses were carried out using the same procedures as in initial soil characterization (Chapter 2) and as in glasshouse study (Chapter 3).

The Degree of P saturation (DPSox) of the soil was calculated as in Equation 4-1.

$$DPSox\ (\%) = [(Ox\text{-}P)/\alpha(Ox\text{-}Al + Ox\text{-}Fe)]*100 \qquad \text{(Equation 4-1)}$$

All concentrations are in mmoles and $\alpha = 0.55$ (Nair et al., 2004).

Soil P storage capacity (SPSC) was also calculated from the oxalate extractable P, Al, and Fe as in Equation 4-2.

$$SPSC\ (mg\ P\ kg^{-1}) = (0.15 - PSR)*(Al_{ox} + Fe_{ox})*31 \qquad \text{(Equation 4-2)}$$

$$PSR = P\ saturation\ ratio = (P_{ox})/(Al_{ox} + Fe_{ox}) \qquad \text{(Equation 4-3)}$$

Where P_{ox}, Al_{ox}, and Fe_{ox} are 0.2M oxalate extractable P, Al, and Fe, respectively.

Plant Samples and Analysis

Plants were harvested twice (July and October) in 2003, and four times (July, August, October, and November) in 2004 from each plot. The grass cuttings were obtained by laying out a 1m by 1m frame on each plot, and all the grass within the frame cut with hand shears to a height of 5cm above the ground surface. Bahiagrass cuttings were then placed in pre-weighed bags, and dried for several days to constant weight at 65°C. Dried materials were afterwards weighed for yield determinations, and sub-samples ground in a Wiley mill with stainless steel blades to pass a 20-mesh sieve. The ground plant samples were stored in airtight polyethylene containers for chemical analysis. Sub-samples of ground plant materials were ashed, treated with 6M HCl, and brought to final volume with distilled water as described by Plank (1992). Colorimetry was used for P determination in the diluted digests (Murphy and Riley, 1962), and Al content determined in digests by ICAP. The plant P and Al uptake values (expressed as kg ha^{-1}) were obtained as the product of concentration (mg kg^{-1} plant) and dry matter yields (kg plant ha^{-1}).

Statistical Analysis

Soil and plant data were analyzed by analysis of variance (ANOVA) as randomized complete block experiments using the GLM procedure and the means separated by contrast procedures in SAS (SAS Institute, 1999). The Tukey test was also used to compare the treatments means, including control treatments, where necessary using one factor (treatment) model: $Y_{ij} = \mu + \alpha_i + \varepsilon_{ij}$; where α_i is effect of i^{th} treatment and ε_{ij} is the error terms. All statistical analysis tests were done at a significance level of 5%. The correlations between soil extractable P and plant parameters and other statistical tests were done using correlation procedure in SAS and Excel software.

Results and Discussion

Impacts of WTR and P-source Rates on Soil P

The subsurface horizons were not affected by the surface applied treatments; rather, the soil P values (WEP, ISP, M-1P, Total P, and Oxalate P) of E and Bh horizon reflected natural variability of the site (data not shown). Thus, the surface applied amendments had no impact on the chemical properties of the subsurface E and Bh-horizons. In the event of P leaching, P likely moved freely through the E-horizon. Further discussions focus on changes in the A-horizon, where treatment effects were observed.

Both WEP and ISP values were consistently reduced by WTR addition in all the A-horizon samples (0-5 and 0-15cm) throughout the study (Table 4-1). The WEP is a good estimate of soil soluble P, and ISP was developed to estimate biologically available P (Menon et al., 1997). The effectiveness of surface applied WTR at reducing soluble P levels of the surface soil will ensure reductions in bioavailable P loss from the soil and, hence, should prevent eutrophication of the nearby aquatic systems.

Analysis of variance (ANOVA) indicated the M-1P values of soil samples taken from 0-5 cm depth was not affected by P-source, source rate, or WTR. The M-1P values were similar for plots with and without WTR at the two P-source rates in soil samples taken from 0-5 cm between June 2003 and December 2004, and in samples taken from 0-15 cm in March 2004, but greater than in control (Fig. 4-1). The general trend of the absolute M-1P values, especially in 0-15 cm samples was: greatest value at N-based with WTR, and least in control treatment.

Table 4-1 Effects of water treatment residual (WTR) on water extractable P (WEP) and iron strip P (ISP) values of A-horizon soils sampled between June 2003 and December 2004. All concentration values are expressed in mg kg^{-1} soil.

Soil P	WTR rates	<---------A-horizon (0-5cm)-------->			<A-horizon (0-15cm)->	
		June 03	Jan. 04	Dec. 04	March 04	Dec. 04
WEP	0%	25.7† a	14.8 a	16.2 a	11.8 a	12.1 a
	1%	6.23 b	4.68 b	5.13 b	5.55 b	4.71 b
ISP	0%	29.7 a	20.8 a	18.5 a	13.7 a	15.2 a
	1%	16.7 b	9.74 b	14.0 b	8.95 b	11.1 b

†Means of 24 samples. Each measure of soil soluble P (WEP or ISP) of samples taken during the same period with similar letter are not different at 5% significance level by Tukey test.

The similar M-1P values in WTR treated and untreated soils likely reflected partial solubilization of the WTR- sorbed P by the acidic extractant, and results were consistent with those observed in the glasshouse study.

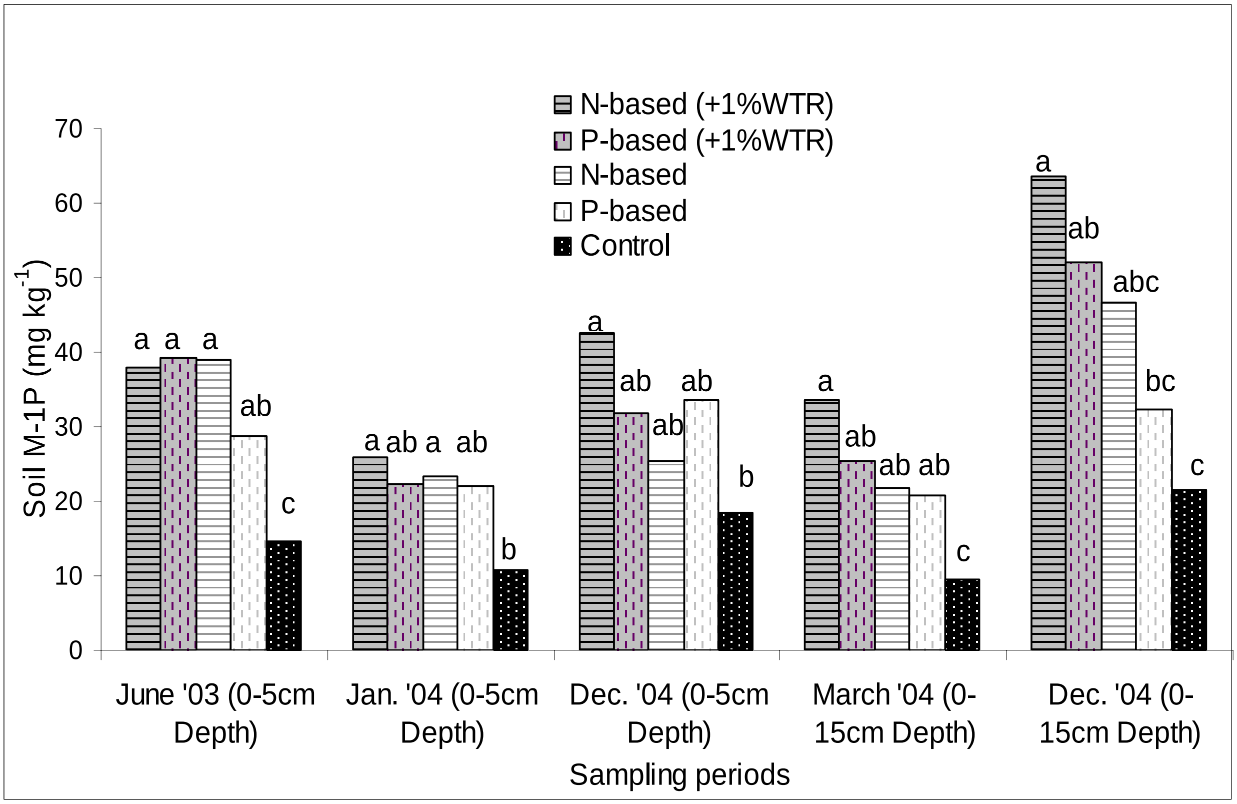


Figure 4-1 Effects of water treatment residual (WTR) rates and P-source rate on Mehlich 1 P (M-1P) values of A-horizon soils at each of the sampling periods (n = 12). Treatments within the same sampling period with the same letters are not different at $p = 0.05$ by Tukey test.

Total recoverable P (TP) values, a measure of soil P loads, were greater in WTR treated than untreated soils (Table 4-2) and reflect both P added as part of the WTR and the WTR-sorbed P. The difference between TP of WTR treated and untreated plots (>100 mg kg^{-1}) was greater than the estimated increase in soil TP attributable to P in the added WTR (27 mg P kg^{-1}), which suggest P retention in WTR-treated soils and losses in untreated plots. The greater P loads in WTR treated than in untreated soils agrees with results of the glasshouse study (Chapter 2), and earlier findings of the capability of the WTR to sorb and retain soil P (O'Connor et al., 2000).

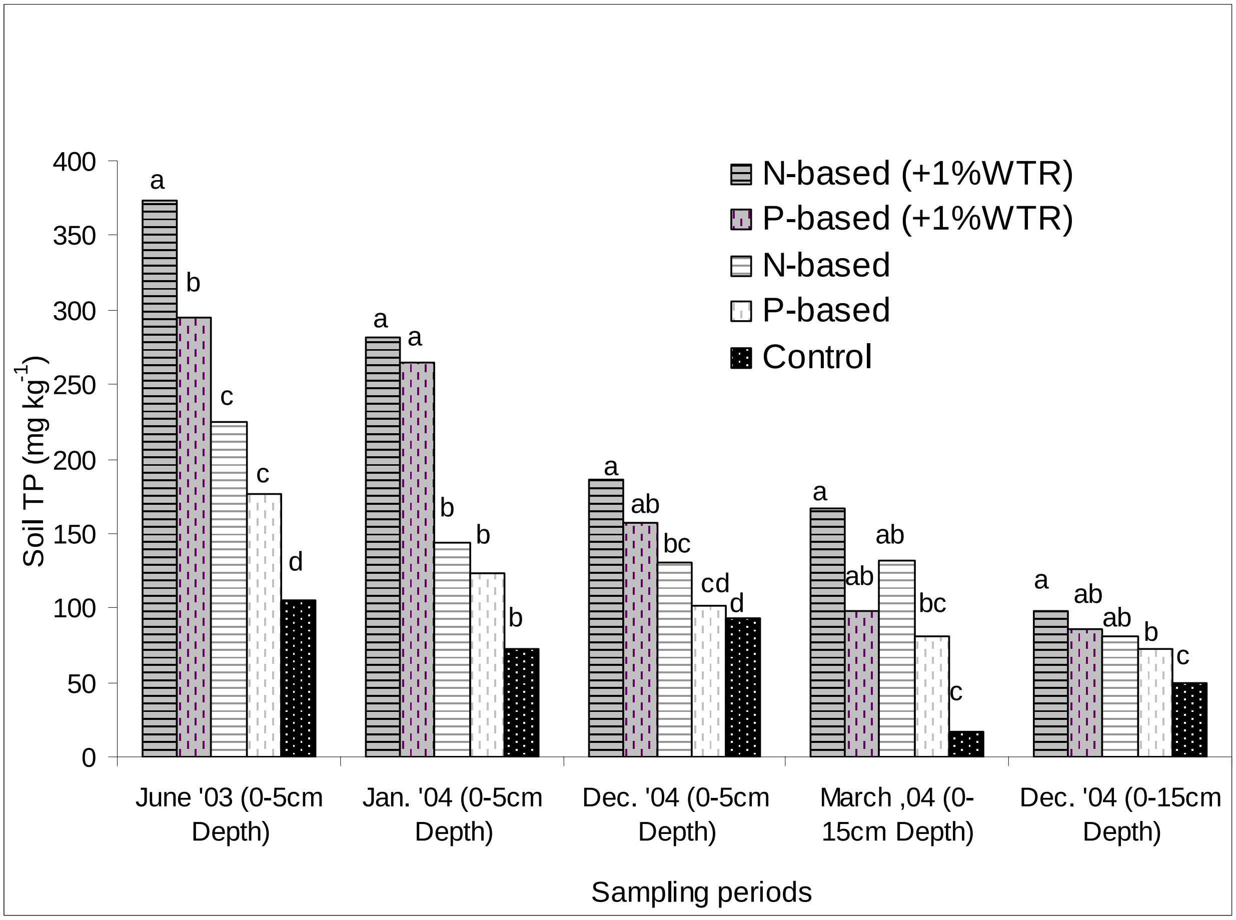


Figure 4-2 Effects of WTR rates and P-source rates on Total P (TP) values of A-horizon soils at each of the sampling periods. (Treatments within the same sampling period with the same letters are not different at $p = 0.05$ by Tukey's test).

Analysis of variance (ANOVA) indicated that neither the application rates, nor the P-sources affected soil soluble P values (WEP and ISP) throughout the study. Values of WEP and ISP were similar for the two rates (N-and P-based) in the absence of WTR, which may be due to loss of soluble P in proportion to the initial levels. Similarly, soil soluble P, as indicated by WEP and ISP values, were not different for the two P-source application rates when WTR was applied, but were consistently smaller than in the absence of WTR (Fig. 4-3a,b). The similar soluble P measures at the two P-source rates established that the effect of application rates could be masked by adding WTR to the soils. The soil WEP values of the N-based rate treatments were reduced when WTR was added, and were similar to the soluble P value observed in the control.

The observed reductions in soil soluble P values (Fig. 4-3a and b) and increases in soil TP values (Fig. 4-2) when WTR is applied are internally consistent and can be explained by the reduction of soil DPS values with addition of WTR throughout the study (Fig. 4-3c). In the A-horizons (0-5 cm), DPS values were reduced to below 25%, identified as critical for Florida soils by Nair et al. (2004). The sorption and retention of the excess added P by WTR was reflected in greater soil TP values in WTR treated than in untreated soils (Fig. 4-2). Thus, as observed in the glasshouse study, the P hazard associated with the N-based P-source application rates could be reduced, below that of the environmental friendly P-based rate by adding WTR.

In the absence of WTR, absolute WEP values were reduced more between June 2003 and January 2004 than between January and December 2004. However, the soil WEP values were similar at all sampling periods for soil treated with WTR. Thus, in the absence of WTR, the low sorbing soil lost substantial soil soluble P, and total soil P values decreased with time. In the presence of WTR, soil WEP values were stable at ~5 mg kg^{-1} with time. Also, ISP values of the A horizon soil samples (0-5cm and 0-15cm) were generally reduced with time except in WTR treated soils.

The proportion of Total P that is water extractable (percentage water extractable or PWEP) was reduced by WTR at both rates in samples taken during the glasshouse and field studies. Added WTR reduced soil PWEP values below 10% in all the samples at both WTR rates during glasshouse and field studies (Table 4-2). Soil PWEP was greater in the absence of WTR than in the presence of WTR in field and the glasshouse study.

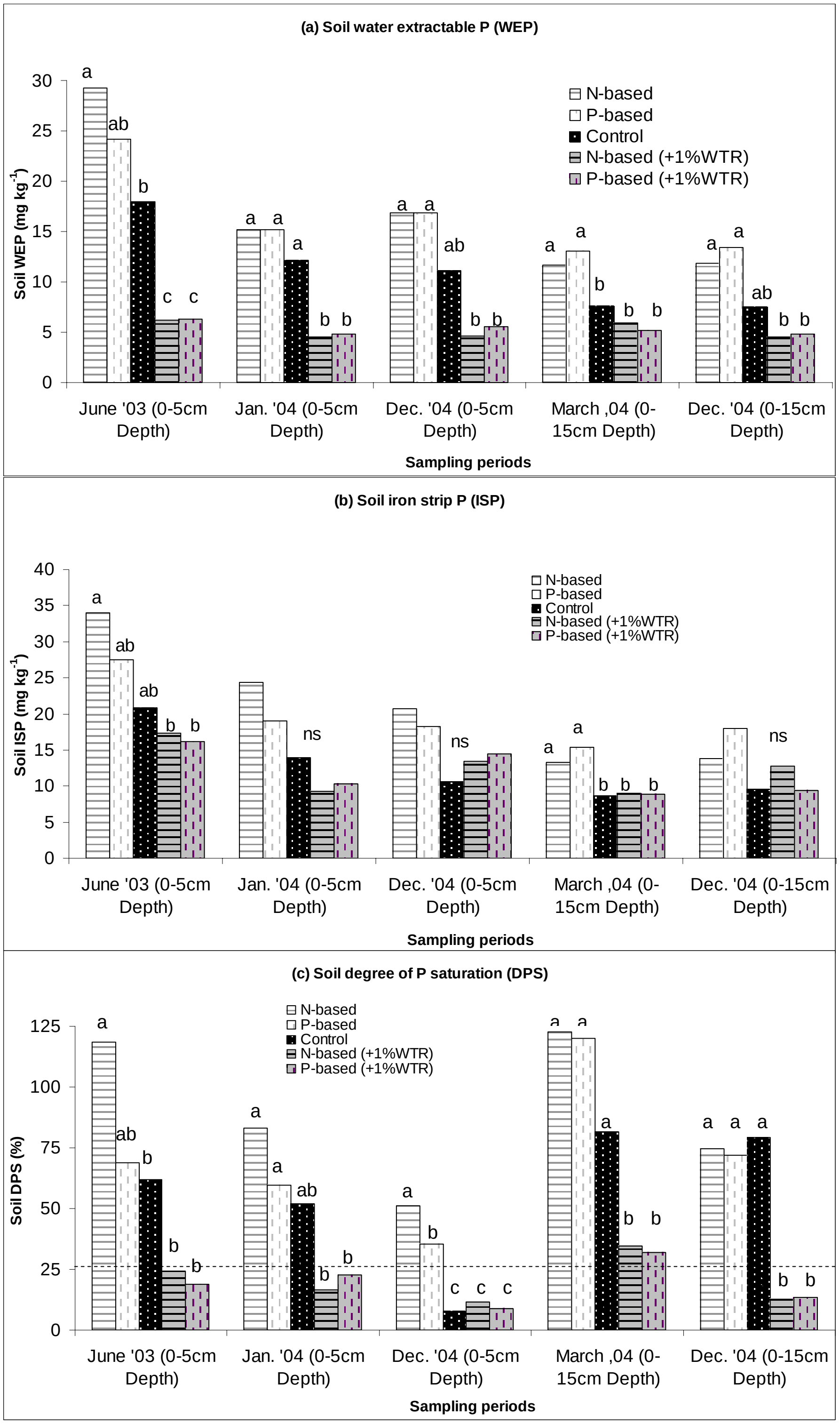


Figure 4-3 Effects of WTR rates and P-source rates on (a) water extractable P (WEP), (b) Iron strip P (ISP), and (c) degree of P sorption (DPS) values of A-horizon soils at each of the sampling periods. (Treatments within the same sampling period with the same letters are not different at $p = 0.05$ by Tukey's test).

Table 4-2. Mean (n = 12) percent water extractable P (PWEP) values of soil samples taken during the glasshouse and field studies, as affected by WTR at the two P-source rates. All PWEP values are expressed in %.

Study	Sampling depth	Sampling date	0% WTR		1%WTR		2.5% WTR	
			N-based	P-based	N-based	P-based	N-based	P-based
Glasshouse	†N/A	June '04	‡16.9 a	15.6 a	9.00 b	6.40 c	4.40 cd	3.10 d
		Dec. '04	22.3 a	17.8 a	5.10 b	4.60 b	3.10 b	3.00 b
		May '05	11.4 a	5.30 b	1.94 b	1.77 b	1.40 b	1.14 b
		Sept. '05	4.74 a	4.13 a	1.48 b	1.44 b	0.99 b	0.77 b
Field	0-5 cm	June '03	12.8 a	13.9 a	1.56 b	2.20 b	N/A	N/A
		Jan. '04	11.3 a	13.2 a	1.90 b	1.98 b	N/A	N/A
		Dec. '04	13.3 a	16.9 a	2.63 b	3.58 b	N/A	N/A
	0-15 cm	Mar. '05	10.1 b	17.3 a	3.95 c	6.03bc	N/A	N/A
		Dec. '05	15.3 a	18.9 a	4.80 b	5.73 b	N/A	N/A

†Not applicable.
‡Means follow by same letter in each row (same sampling period) are not different at 5% significance level by Tukey test.

Impacts of P-Sources on Soil P

Analysis of variance indicated that soil soluble P values (WEP and ISP) were not affected by the sources of P. However, soil Total recoverable P values differed for the different P-sources (ANOVA Table).

Impacts of the P-sources on the soil P is better studied in the absence of WTR, where P-sources and application rates are isolated as variables affecting measures of soil P. Soil soluble P (WEP) values were similar for the different P-sources at both source application rates throughout the study (Fig. 4-4a).

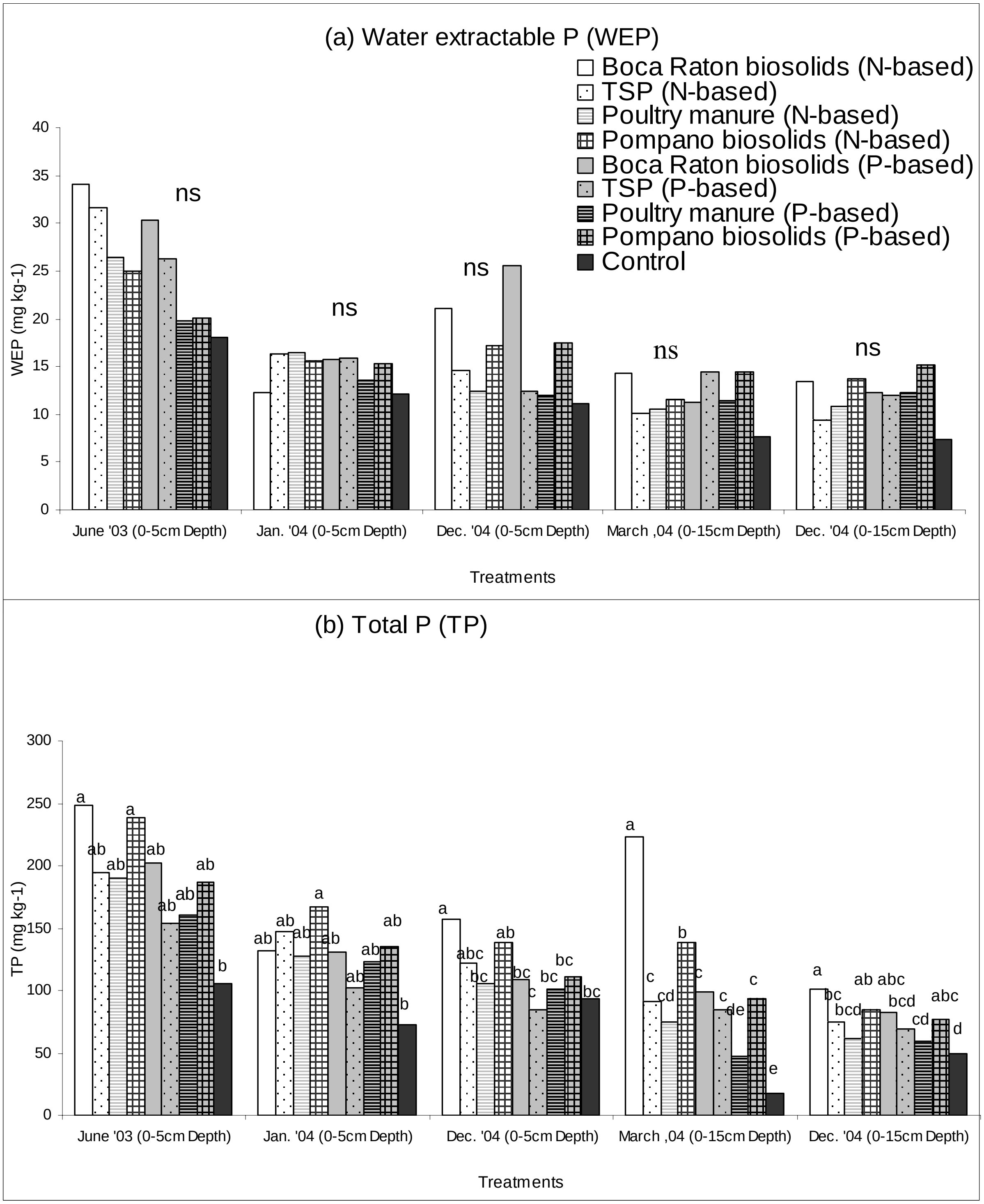


Figure 4-4. Trends of (a) soil water extractable P (WEP) and (b) Total recoverable P (TP) values for treatments with different P-sources at the two P rates in the absence of water treatment residual (WTR). (Treatments within the same sampling period with the same letters are not different at $p = 0.05$ by Tukey's test).

Also, Total P values for samples taken in June 2003 and January 2004 (0-5 cm) were similar for different P-sources, and only different from control treatment. However, samples taken in March and December 2004 from A-horizon (0-15cm depth) indicated greatest soil TP in Boca Raton biosolids and least in control.

Impacts of Treatments on Soil Sorption Properties

The degree of phosphorus saturation (DPS) is an index of how saturated the P sorption sites of soil are and, hence, a measure of soil capability to retain and prevent P losses from the soil through runoff and leaching. Soils with large DPS values indicate the soil sorption sites are saturated and suggest little capability of the soil to retain additional P.

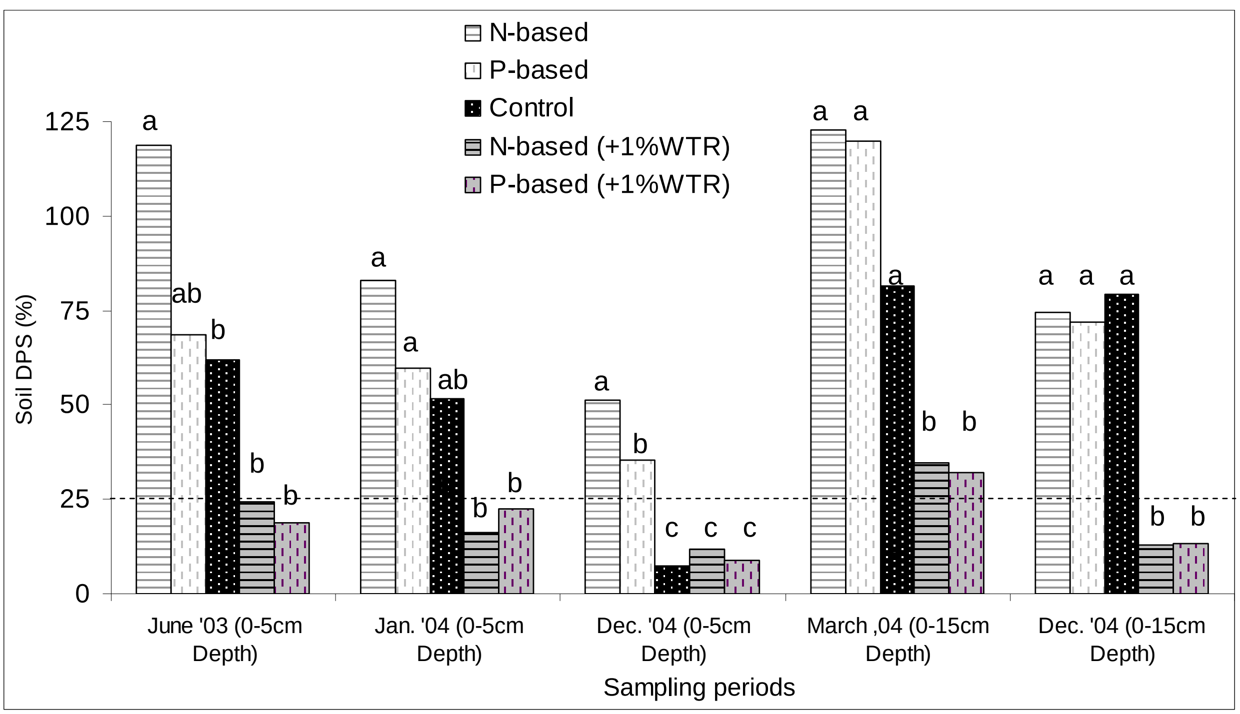


Figure 4-5 Effects of WTR rates and P-source rates on degree of P saturation (DPS) values of A-horizon soils at each of the sampling periods. Treatments within the same sampling period with the same letters are not different at $p = 0.05$ by Tukey's test.

Source of P did not affect the soil DPS value throughout the study. The effects of WTR on soil DPS values at each P-source rate are shown in Fig. 4-5 for the samples between June 2003 and December 2004. The DPS values of all soils not treated with WTR exceed 25%, whereas most WTR amended soils have DPS below the critical value of ~ 25% suggested for Florida soils (Nair et al., 2004). The reduced soil DPS values in the presence of WTR are consistent with the observations from the glasshouse study, and confirm the ability of the WTR to enhance the sorption properties of the sandy, low P-sorbing Florida soils.

The increasing soil sorption sites indicated by reduced DPS values are consistent with reduced WEP values (Fig. 4-6). The soil WEP values are expected to indicate potential for soil P loss through runoff (Pote et al., 1999; Vadas et al., 2006), and leachate (Kleinman et al., 2000). The WEP values were lower than 10 mg kg^{-1} in soils receiving WTR, but ≥ 10 mg kg^{-1} in soils without WTR, throughout the study (Fig. 4-6). Also, a change point can be identified by Cate-Nelson (1977) type of approximation at ~25% DPS. Above 25% DPS, most soil WEP values were ≥ 10mg kg^{-1}, but the WEP values were lowered than 10 mg kg^{-1} below 25% DPS.

The WEP values were also shown to relate well with DPS values by Nair et al. (2004) in Florida soils. A threshold (change point) value of ~25% was also observed by Breeuwsma et al. (1995) in sandy soils of the Netherlands, while ~20% was identified as the threshold DPS value for Florida soils by Nair et al. (2004). The relationship between M-1P values and DPS_{ox} values indicated that DPS_{ox} values of 22% and 28% are equivalents to 20 mg kg^{-1} M-1P (agronomic high) and 50 mg kg^{-1} M-1P (very high) values, respectively. Irrespective of the P-source application rates, the DPS values of treatments receiving no WTR were greater than 25% throughout the two year study. This suggests that applying any P-source, even at P-based rates, could increase the risk of P loss. However, applying WTR could mask the effects of both the source and rate of P applied, and, hence, dramatically reduce P loss potential.

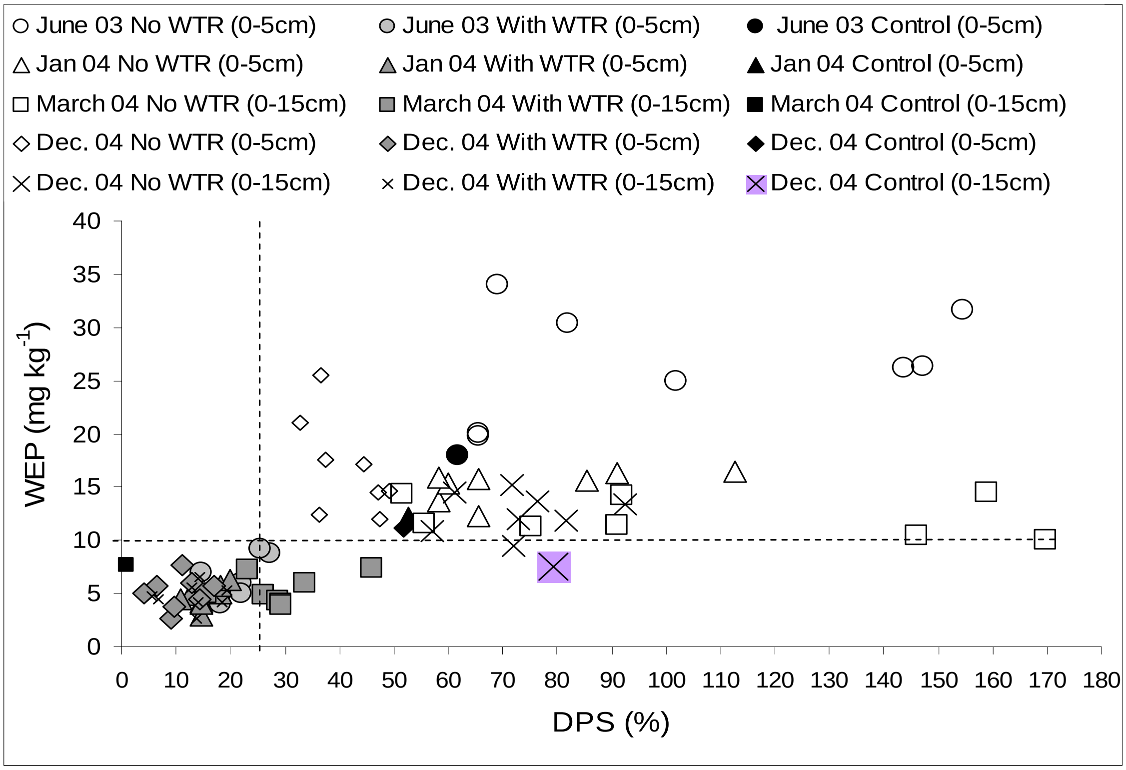


Figure 4-6. Soil water extractable P (WEP) values as affected by degree of P saturation (DPS) values of soil samples taken between June 2003 and December 2004 (Vertical dotted line locates the 25% DPS environmental threshold.

Soil phosphorus storage capacity (SPSC) values of samples taken in June 2003, January 2004 and December 2004 from the three soil horizons are shown in Fig. 4-7 (E and Bh horizons) and Fig. 4-8 (A-horizons). The minimal impact of the surface applied treatments on soils in the subsurface horizons is established by the similar SPSC values of the E and Bh horizons for all treatments, irrespective of the sampling period (Fig. 4-7). The SPSC values of the E-horizon soil samples are similar and negative (or approximately zero). Such values indicate near saturation of P sorption sites on the soils and inability to retain added P (Nair and Harris, 2004). The SPSC values of the Bh horizon samples were similar and positive (~147 mg kg^{-1}) for all treatments.

Positive SPSC values, an indication of soil capacity to retain added P, are expected of the Al-rich Bh-horizon, and the similarity of the values for the different treatments over time reflects the minimal effect of the surface-applied treatments.

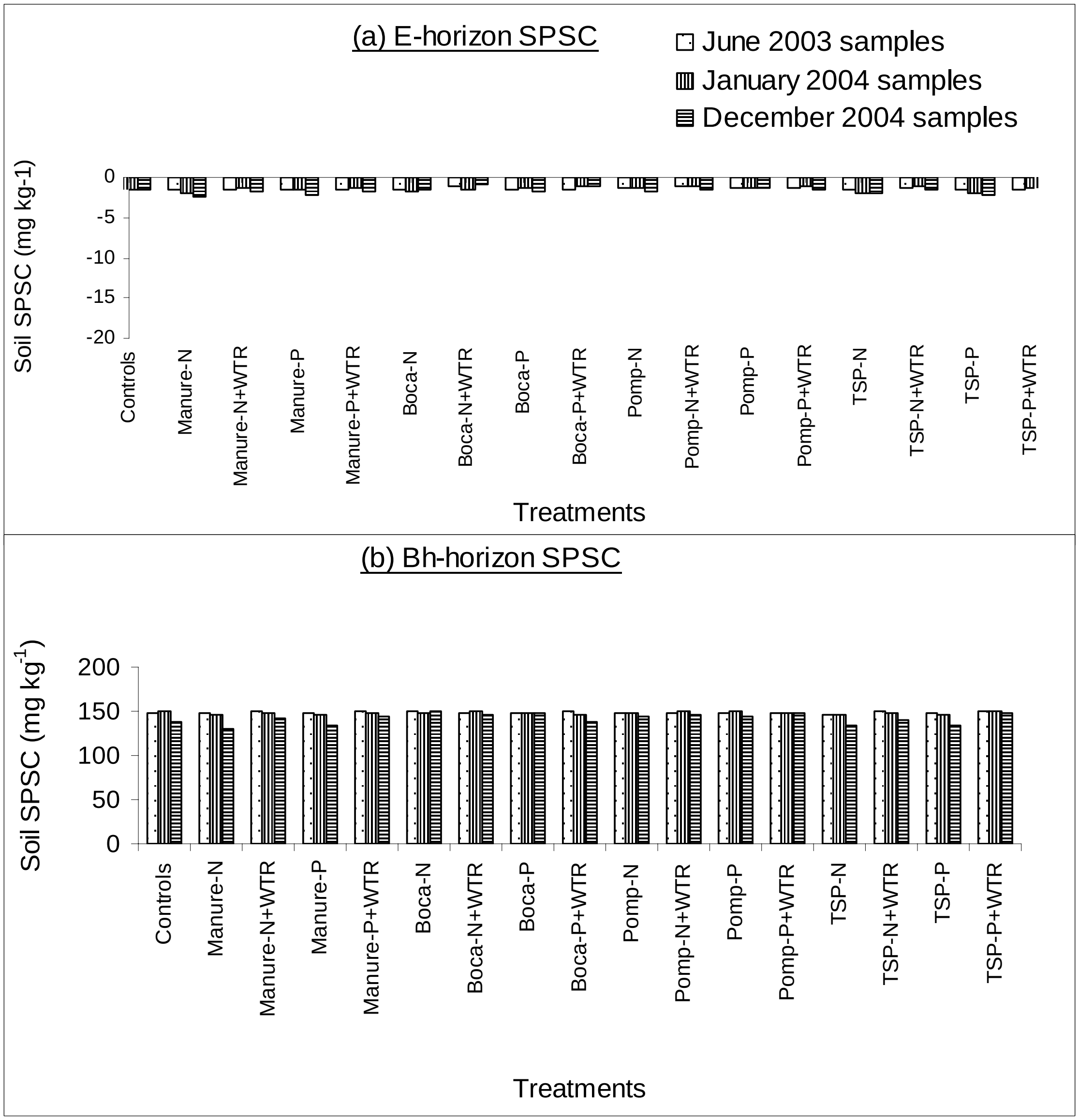


Figure 4-7. Soil phosphorus storage capacity (SPSC, mg kg^{-1}) values of subsurface (E and Bh horizons) samples from the field study (June 2003 – Dec. 2004). Note the differences in scales of the 2 figures. (There were no significant treatments effects (P-source, P rate or WTR) at $p = 0.05$ on SPSC values of E and Bh horizon soil sampled at any time during the study (ANOVA)).

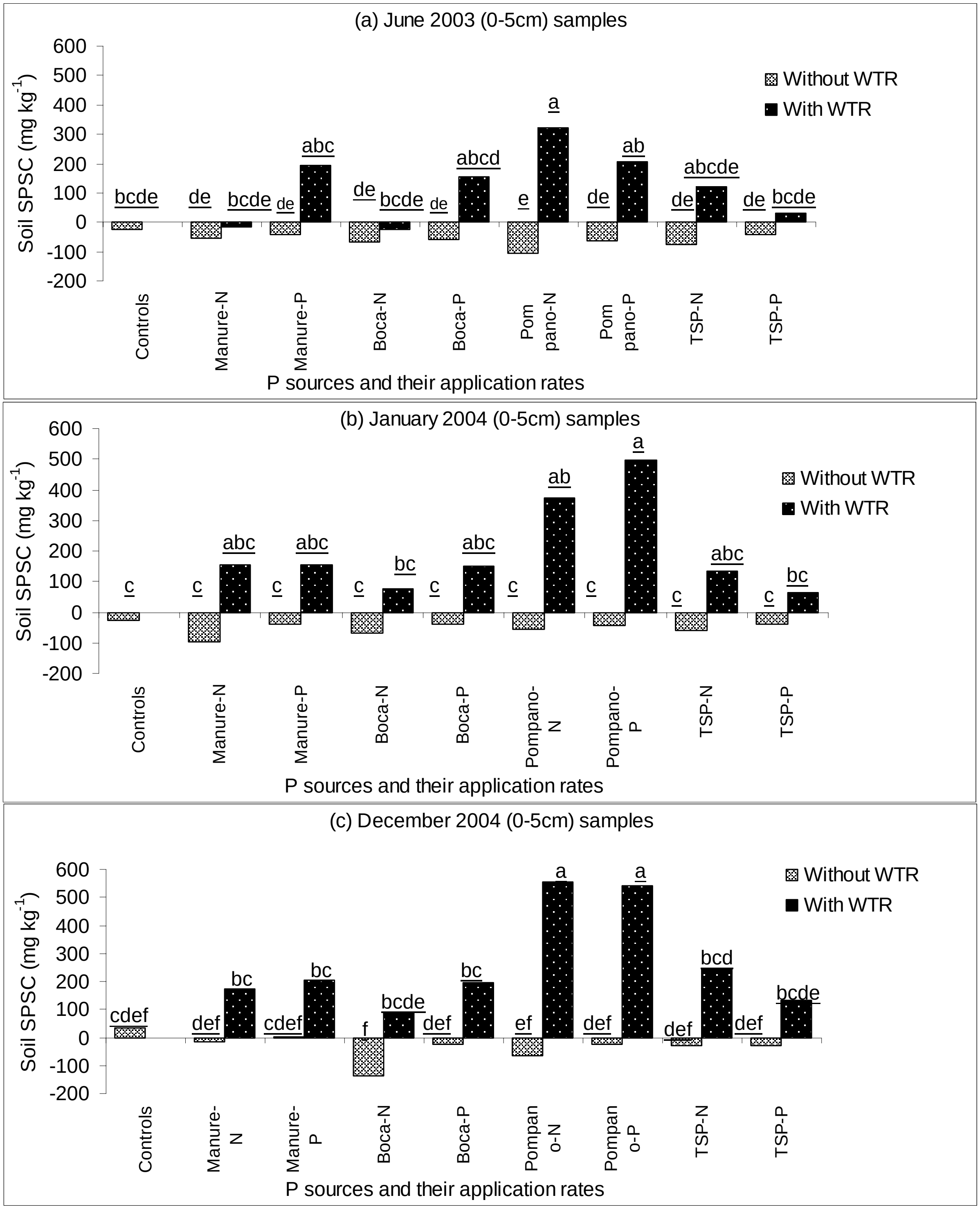


Figure 4-8. Soil phosphorus storage capacity (SPSC, mg kg^{-1}) values of A-horizon (0-5cm) samples from the field study (June 2003 – Dec. 2004) as affected by the treatments. (Treatments ending in P, and N, are P-based and N-based rates of the sources, respectively). Treatments with the same letters are not different at p = 0.05 by Tukey test.

The impacts of the surface applied treatments were obvious in the SPSC values of samples from A-horizons (0-5cm). Similar to observations in the glasshouse study, soil samples from plots amended with P-sources without WTR had negative SPSC values, and SPSC values for the N-based treatments were more negative than for P-based treatments (Fig 4-8). Thus, when the soils are amended with P without WTR, the P-storage capacity was reduced more (more negative SPSC value) at N-based rates than at P-based rates. Similar to the trends of the DPS data, the SPSC values (and, hence, P sorption properties) were improved by addition of WTR. The more positive the SPSC value, the greater the P sorption capacity.

Impacts of Treatments on Plants

Plant dry matter yields, yield-weighted P concentrations, and P uptake data for the 2003 and 2004 harvests are summarized in Figure 4-9. The greater variability in the dry matter yields of 2003 than in 2004 likely reflected natural, nutritional variations in the fields before treatment applications, and before some treatments took effect. The yields of the two years were similar (for each treatment) even though harvesting was done two times in 2003 compared to four times in 2004 and treatments were applied only in 2003, at the start of the study

The yield-weighted P concentrations were reduced with addition of WTR for each P-source, and source application rate during both growing seasons. The reduced plants P concentrations agree with the results from the glasshouse study. Other studies also indicated reductions in plant P concentrations with addition of WTR (Heil and Barbarick, 1989; Elliott and Singer, 1988), and suggest that not all P sorbed by WTR is accessible by the plant. However, all plant P concentrations in the field study were above the critical level, as indicated by the uniform yields.

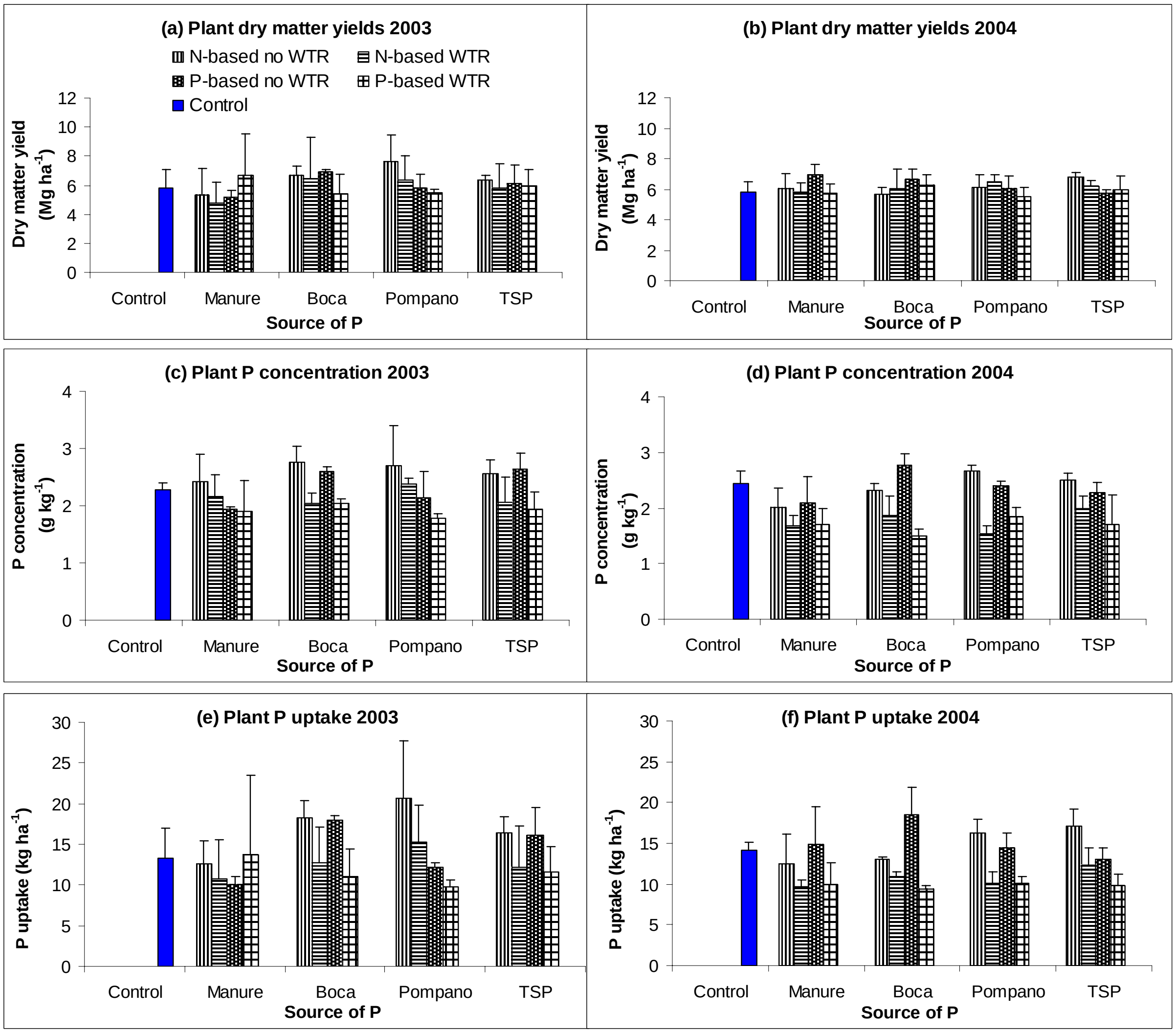


Figure 4-9. Plant dry matter yields (Mg ha^{-1}), yield-weighted P concentrations (g kg^{-1}), and P uptake (kg ha^{-1}) from 2003 and 2004 harvests (Error bar represent one standard deviation (n =3)).

Plant P uptake in 2003 was not affected by the source of P or P-source rates, but the P uptake was reduced in plots treated with WTR. In 2004 harvests, P uptake was not affected by WTR treatments at the N-based rates of manure or TSP (Table 4-3), but reduced P uptake by WTR at N-based rates of the two biosolids, and at P-based rate of all P-sources were observed. The trend of P uptake supports the findings from the glasshouse study that applying WTR to P-based treatments will reduce the P uptake, irrespective of the P-source applied.

Table 4-3. Effects of P-sources, P-source rates, and water treatment residual (WTR) rates, on plant P uptake (kg P ha^{-1}) values of bahiagrass harvested in 2004.

Source of P	WTR Rate / Contrast	------------Rate-------------		Contrast
		N-based	P-based	N-based vs. P-based
Manure	0%	12.4†	14.8	NS
	1%	9.7	9.9	NS
	Contrast	NS	*	
Boca Raton biosolids	0%	13.0	18.5	*
	1%	10.9	9.4	NS
	Contrast	*	*	
Pompano biosolids	0%	16.3	14.5	NS
	1%	10.0	10.1	NS
	Contrast	*	*	
TSP	0%	17.1	13.1	*
	1%	12.3	9.8	NS
	Contrast	NS	*	
Contrast (At 0% WTR)	Manure vs. Biosolids	NS	NS	
	Organic vs. Mineral	*	NS	
	Boca Raton vs. Pompano	*	NS	
Contrast (At 1% WTR)	Manure vs. Biosolids	NS	NS	
	Organic vs. Mineral	*	NS	
	Boca Raton vs. Pompano	*	NS	

† Means of three samples
* Significant at $p = 0.05$ by contrast
NS not significant at $p = 0.05$ by contrast

In addition to the effect of WTR, P uptake was also affected by the source of P, and P-source application rates in 2004 (Table 4-3). In the absence of WTR, P uptake from TSP treated plots was greater at N-based rates than at P–based rates, which reflects the greater initial P loads of the N-based rates. Phosphorus was applied only once (in 2003) and, at the P-based rate, is not sufficient for growth in the following year (2004). However, at the N-based rate, the excess P applied in the 2003 was apparently sufficient to sustain plant growth through 2004. Plant P uptake values were similar at the two P rates for all sources of P when WTR was applied. Thus, similar to the effects on the soil soluble P values, WTR apparently masked the effects of P-source rates on plant P uptake, irrespective of the P-source applied.

Phosphorus uptake values were also similar for treatments with different P-sources at each of the two levels of WTR at P-based rate. In the N-based treatments, P uptake was greater in TSP-treated than organic source of P-treated soils at each level of WTR. In the absence of WTR, and at the N-based rate, greater P uptake was observed in Pompano than in Boca Raton biosolids treated plots. The greater loss of soluble P from the high water soluble P Boca Raton biosolids treated soils, than from the moderate water soluble P Pompano biosolids treated soils, could have resulted in greater P uptake from Pompano biosolids than from Boca Raton biosolids treatments. The glasshouse study also indicated that, in the absence of WTR, Pompano biosolids could mimic slow release fertilizer as regards P release to plants. The greater P uptake in Boca Raton biosolids than in Pompano biosolids treatments at N-based rate (and at 1%WTR) suggests a portion of the WTR-sorbed P from the high water soluble P Boca Raton biosolids is accessible by the plants.

The yield-weighted P concentrations in 2003 harvests were greater at N-based rates than P-based rates, and greater in the absence than in the presence of WTR. However, in the 2004 harvests, there were greater plant P concentrations in the absence than in the presence of WTR. Greater plant P concentrations in WTR treated than untreated soil in 2004 suggested that a portion of P retained in the soil by the WTR is accessed by the plants. Despite the reduction in plant P concentrations by added WTR, plant yields were not affected in either growing seasons (Fig. 4-10). The plant yields of 2003 and 2004 were also not affected by source of P, nor the source application rates. This indicates sufficient plant P concentrations for optimum growth of the plant.

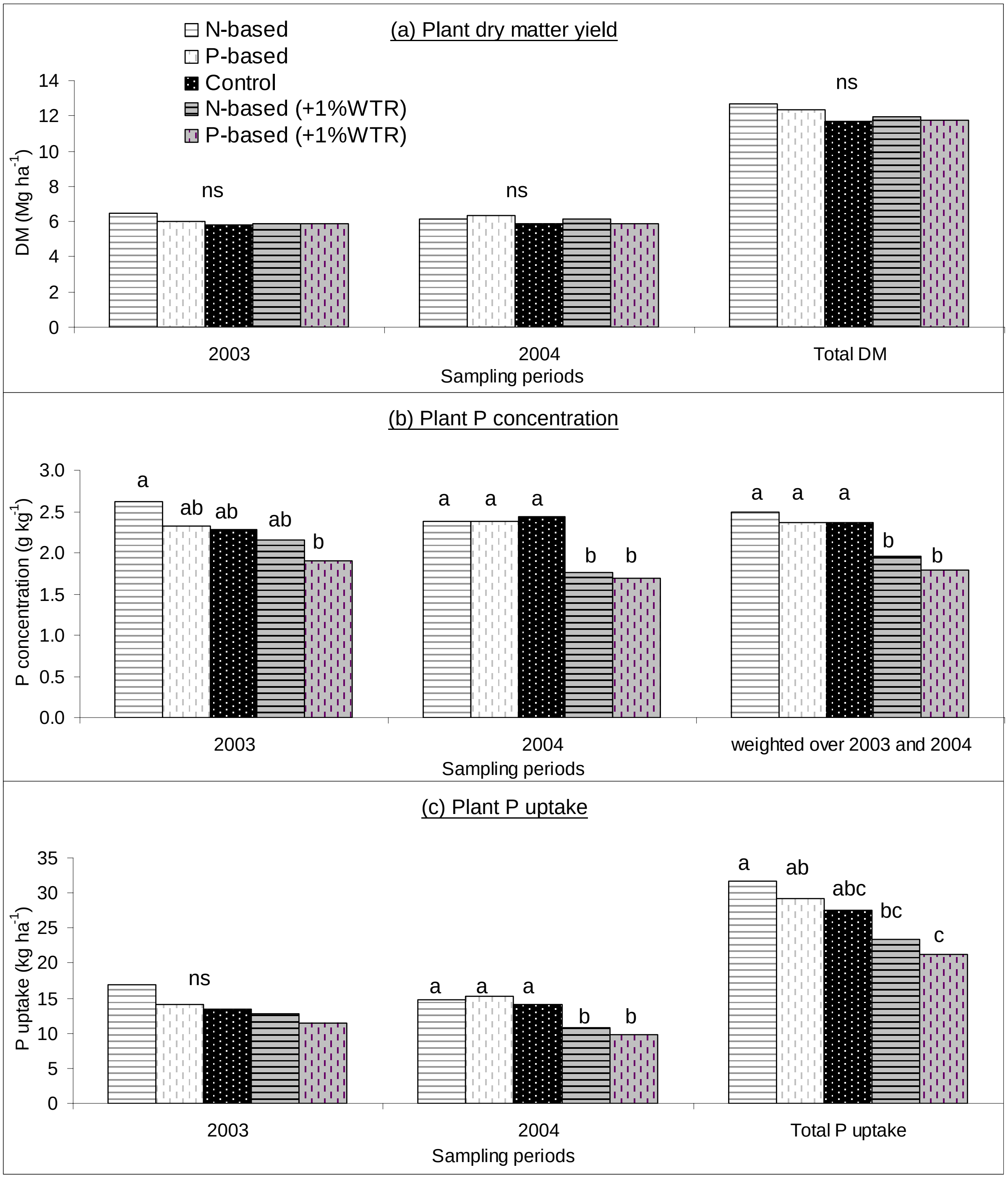


Figure 4-10. Effects of water treatment residual (WTR) rates and P-source rates on plant DM yield, P concentration and P uptake. (Treatments within the same sampling period with the same letters are not different at $p = 0.05$ by Tukey test).

In summary, applying WTR increased P sorption of the low P-sorbing soil and, thereby, reduced soil soluble P (Fig. 4-10). Plant yields were not affected by the reduced soil soluble P, nor by the reduced plant P concentrations (Fig. 4-10). Thus, the readily desorbable P and P potentially available for loss to runoff and leachate were reduced by amendment with WTR. Improving the P sorption property of a soil with WTR is expected to have no negative effects on the yield, though plant P uptake may be reduced. Thus, similar to the observations in the glasshouse study, we fail to reject the null hypothesis, and conclude that applying WTR to N-based rates of P-sources reduces negative environmental P impacts and optimizes the agronomic benefits (as in P-based rates without WTR).

Plant and soil data from both glasshouse and field study established that problems of excessive soluble P associated with high P rate (N-based) can be controlled without affecting bahiagrass yields.

Relative Phosphorus Phytoavailability (RPP)

The observed reductions in soil soluble P with time could be due to P uptake, increased P retention by WTR, and P loss. Thus, the relative availability of P from organic sources to plants, compared with mineral fertilizer, is better studied in the absence of WTR and where P losses can be quantified. The differential P loss in the absence of WTR was minimal in the first growing season compared to the 2004 growing season as indicated by the trend of soil TP (Fig. 4-2). Thus, the 2003 data with minimal P loss were regarded as most appropriate for comparing the P-sources.

The "relative P phytoavailability" (RPP) was calculated for each P-source at P-based rates without WTR. The P-based rates supplied equal amounts of P from the different P-sources to the plants (unlike the N-based rate), and all plots were supplied with adequate nitrogen. The P loss was accounted for by averaging time zero and time final total soil P concentrations for the 2003 growing season and P uptake calculated per unit of average soil P for each source. The P uptake per unit of soil P from plots treated with different P-sources was then divided by similar ratio obtained for the TSP treatment to arrive at RPP expressed in percentage for each P-source. The different P-source treatments were related to the TSP treatment because it contained sufficient readily available mineral P, and was expected to give optimum agronomic performance

Thus, RPP were calculated as in Equation 4-4.

$$RPP = \frac{(P\ uptake_{source}/Average\ soil\ P\ conc._{source})}{P\ uptake_{TSP}/\ Average\ soil\ P\ conc._{TSP}} * 100 \qquad (Equation\ 4\text{-}4)$$

The RPP values obtained for the organic sources of P ranged from 55% for poultry manure to 85% in Boca Raton biosolids (Table 4-4). Most biosolids evaluated by de Haan (1981) were between 36 and 90% as phytoavailable as fertilizer P.

Table 4-4. Relative P phytoavailability (RPP) values for the different P-sources during the field study.

Source of P	RPP (%)
Manure	55
Boca Raton biosolids	85
Pompano biosolids	59
TSP	100

O'Connor et al. (2004) rated the relative P phytoavailability of various biosolids (compared to TSP), and suggested three classes: high (similar to TSP, RPP >75%), moderate (RPP = 25 – 75%), and low (RPP <25%). Values of RPP differed with biosolids processing, total Fe, and Al concentrations, and %solids content. Results from both the glasshouse and field studies (Table 4-5) show the RPP of Boca Raton biosolids compares favorably well with the RPP for TSP, and the biosolids would be regarded as a high RPP organic source. Boca Raton biosolids are produced via a process similar to biological P removal process (BPR), which O'Connor et al. (2004) suggested should have high RPP values. Pompano biosolids have characteristics (Table 2-1) that suggests it should have moderate RPP (Total Al + Fe concentration = 42 g kg^{-1}; PSI = 0.7). Biosolids of similar properties (e.g., Tarpon Spring cake; Total Al + Fe concentration = 42 g kg^{-1}) studied by O'Connor et al. (2004) also fell into moderate P phytoavailability category.

Table 4-5. Relative P phytoavailability (RPP) values for the different P-sources from field and glasshouse studies. All RPP values are expressed in %.

P-source	<----------------Glasshouse study------------------>				Field study	RPP ‡Category
	Bahiagrass (1)	Ryegrass	Bahiagrass (2)	†Combined		
Manure	30	55	36	43	55	Moderate (25-75%)
Boca Raton biosolids	82	68	82	82	85	High (>75%)
Pompano biosolids	41	55	58	53	59	Moderate (25-75%)
TSP	100	100	100	100	100	High (>75%)

† RPP based on sum of P uptake from the three cropping.
‡ Categorized according to O'Connor et al. (2004).

The data collected from both glasshouse and field studies (Table 4-7) suggest that both Pompano biosolids and manure have RPP representative of the moderate category. The range of the values of moderate RPP P-source category is consistent with 50% suggested for organic source of P by USEPA guidelines (USEPA, 1995). A 67% relative effectiveness of the biosolids used in a recent study by Pritchard (2005) was also reported. The RPP values reported for the varying biosolids studied by O'Connor et al. (2004) ranged between <10% and 100% RPP, compared to TSP. The range of values is similar to the 10 – 100% range reported by de Haan (1988). McLaughlin and Champion (1987) observed >90% RPP for an anaerobically digested biosolids, compared to monocalcium phosphate fertilizer (MCP).

The Quebec Canada regulatory agency proposed short term estimates of P availability from biosolids (%$P_{available}$) can be calculated using Equation 4-5 (Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ), 2003; Québec Ministère de l'Environnement (MENV) 2003):

$$\%P_{available} = 70-\{concentration\ (Al_{total} + 0.5\ Fe_{total}\ [mg\ kg^{-1}]) - 20{,}000\}/2000 \quad \text{(Equation 4-5)}$$

The equation has not been field validated, and is based on the following assumptions:

- For biosolids not treated with Al or Fe salts, P availability is about 70% that of mineral fertilizers. Manure P availability also ranges from 65-80% compared with mineral fertilizer.
- With increasing Al and Fe content, biosolids P availability is assumed to decrease linearly to an arbitrary value of 5% for an Al + 0.5 Fe content of 150,000 mg kg^{-1}.
- An Al + 0.5 Fe content of 20,000 mg kg^{-1} represents the background content of biosolids with no Al or Fe salt added.

(Note that Al and Fe both have valences of +3, and atomic weights 27 and 56, respectively and, hence, Al is equivalent to 0.5 Fe).

Using Equation 4-5, the %$P_{available}$ obtained for the organic source of P used in this study are 79% (poultry manure), 69% (Boca Raton biosolids), and 67% (Pompano biosolids). The %$P_{available}$ obtained did not agree with the observed RPP, rather it has an inverse relationship with the P-source RPP values measured. The %$P_{available}$ obtained, tracked well (negative correlation) with the Al + 0.5 Fe concentrations (1.65, 21.5, and 25.6 g kg^{-1} for poultry, Boca Raton biosolids, and Pompano biosolids, respectively) of the P-sources which are the only variables used for the estimation. An attempt was made to estimate the RPP of the twelve (12) biosolids used by O'Connor et al. (2004) using Equation 4-5. The calculated %$P_{available}$ values were also very different from the observed RPP values. Thus, the RPP may not be adequately estimated from the $\%P_{available}$ equation suggested by Quebec Canada regulatory agency without accounting for other properties of the P-sources.

Data from the study carried out by O'Connor et al. (2004) with 12 biosolids were pooled with data from this study to identify properties of biosolids that could affect and account for their RPP values. Manure was not included since only one manure type (poultry manure) was used in this study, which is insufficient to make inference about the wide spectrum of manure types. Properties of biosolids determined included Total P, Fe, Al, Ca, Mg, % solids, % organic matter, and C:N. The forms of P in the materials were also characterized by sequential extraction into KCl-P, NaOH-P, and HCl-P fractions. Varying measures of biosolids extractable P (citric acid P, M-1P, WEP, Oxalate-P), percentage water extractable P (PWEP), oxalate extractable Fe, Al, and PSI were also determined. Properties of biosolids that could account for RPP variability were identified by stepwise regression of the observed RPP values with the properties of the P-sources. Altogether, 14 biosolids were considered (including Boca Raton biosolids and Pompano biosolids from this study).

Among the twenty variables used for the regression, only three variables (Total P, NaOH-P, and %solids) were identified by the stepwise regression as affecting the RPP values (Table 4-6 and 4-7). The results indicated that Total P and NaOH-P, could account for ~90% ($r^2 = 0.9$; $p<0.05$) of the variability in RPP values, and 95% of the variability could be accounted for by including %solids of the P-sources. Total-P concentration of the P-sources was identified as the most important variable that could account for the RPP variability. Over 70% of the variability ($r^2 = 0.74$) in RPP values could be accounted for by the Total P concentration. Inclusion of NaOH-P with Total-P concentration improved the regression ($r^2 = 0.90$).

Table 4-6. Stepwise regression of relative P phytoavailability (RPP) values of biosolids with some of the biosolids properties (includes data from O'Connor et al., 2004)

Step	Variable	Estimate	*p*-value (regression parameters)	r^2	*p*-value (regression equation)
1. Total P entered	Intercept	-115	0.0114	0.73	0.0015
	Total P	5.89	0.0015		
2. NaOH-P entered	Intercept	-63.7	0.0555	0.90	0.0003
	Total P	5.17	0.0005		
	NaOH-P	-2.08	0.0113		
3. % Solids entered	Intercept	-42.2	0.1049	0.95	0.0002
	Total P	4.64	0.0004		
	NaOH-P	-1.84	0.0070		
	% Solids	-0.24	0.0398		

Table 4-7. Summary of regression parameters for the variables selected by the stepwise regression of relative P phytoavailability (RPP) values of biosolids with some of the P-sources properties

Regression step	Variable entered	Number of variables in the model	Partial r^2	Model r^2	*p*-value
1	Total P	1	0.74	0.74	0.0015
2	NaOH-P	2	0.16	0.90	0.0113
3	% Solids	3	0.05	0.95	0.0398

The NaOH extractable P represents the Fe- and Al-bound P fraction, which may not be readily available to the plants. The negative regression coefficients associated with the NaOH-P support the negative impact of the P form on RPP value. Thus, the equation suggests Total-P less NaOH-P of the source could account for 90% of the variability in RPP estimation. The NaOH-P term accounts for differences in RPP estimate from the source Total-P by considering Fe and Al composition of the sources, and improves the estimate of RPP values (r^2 = 0.90). The Al and Fe concentrations of the biosolids were also noted as important properties by O'Connor et al.

(2004). The important role of Al and Fe concentrations in biosolids P lability could explain why the two variables were accounted for in an attempt by Quebec Canada regulatory agency to estimate $\%P_{available}$ of biosolids using Equation 4-5 (CRAAQ, 2003; MENV 2003). Another source variable identified as important by the regression analysis was %solids, a physical property of the source that reflects the extent of dewatering used in producing the biosolids. Increasing the %solids by pelletizing biosolids has been reported to reduce their RPP. The RPP of Largo and Baltimore cakes were reported reduced when pelletized by O'Connor et al. (2004). Smith et al. (2002) also indicated that heat drying significantly reduced biosolids P availability.

The present study is not sufficient to recommend estimating RPP of biosolids from the regression equation, but serves to identify P-source properties that could be the focus of further study to arrive at a robust prediction equation for RPP. The study shows that the RPP could be adequately predicted from the source physical and chemical properties (Fig. 4-11).

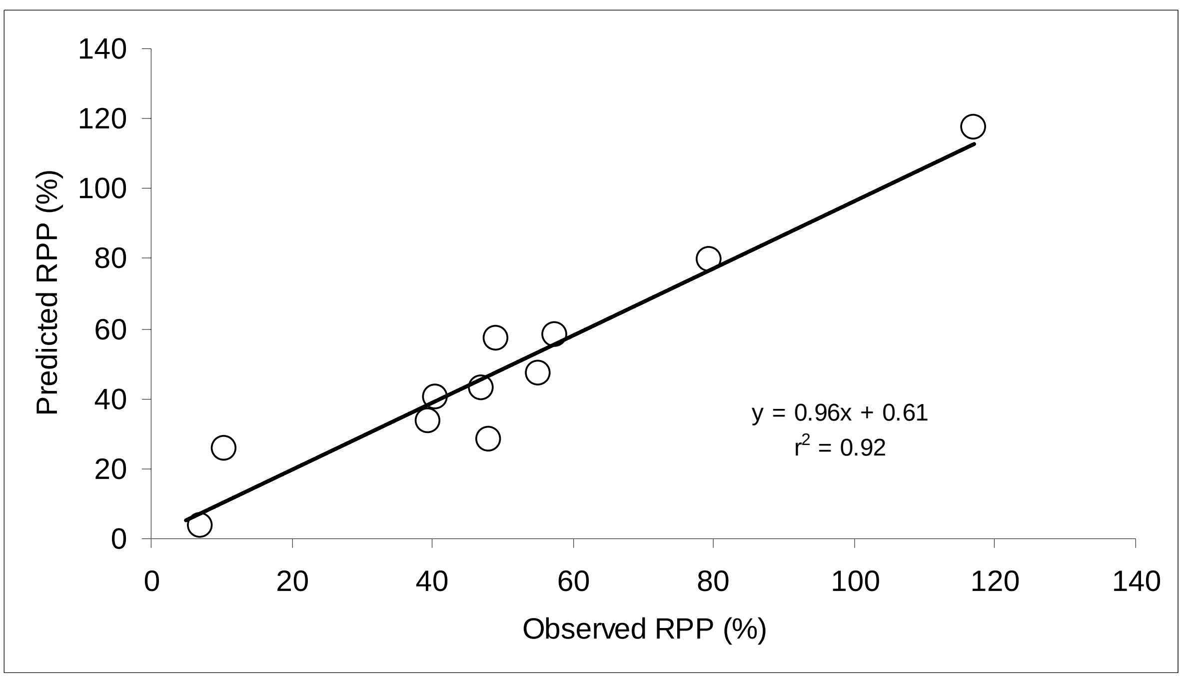


Figure 4-11. The relative P phytoavailability (RPP) as predicted by the Total P, NaOH-P, and %solids values of the biosolids plotted against the observed RPP.

However, the study was largely limited to biosolids applied to a P-deficient Florida sandy soil. Studies with other organic sources especially manure will be needed, as only one manure type (poultry manure) was used in this study, which is insufficient to make inference about the wide spectrum of manure types. Also, as hinted by O'Connor et al. (2004), effects of applying different organic sources to soils with adequate P or large P-retention capacities may be masked.

Aluminum Toxicity

Plant Al concentrations and uptake for each of the harvests in the 2003 and 2004 growing seasons are summarized in Table 4-8.

Table 4-8. Effect of aluminum water treatment residual (Al-WTR) on bahiagrass Al concentrations and uptake during the field study

Planting Season	Parameters	Sampling period	WTR Treatments	
			Without WTR	With WTR
2003	Al concentrations ($mg\ kg^{-1}$)	July	19.3 b[†]	77.2 a
		October	18.8 b	141 a
	Al uptake ($g\ ha^{-1}$)	July	75.6 b	316 a
		October	55.3 b	375 a
		Total	131 b	691 a
2004	Al concentrations ($mg\ kg^{-1}$)	July	41.8 a	70.7 a
		August	13.6 a	12.3 a
		October	5.75 a	8.53 a
		November	32.3 b	123 a
	Al uptake ($g\ ha^{-1}$)	July	103 a	178 a
		August	22.7 a	16.5 b
		October	6.99 a	9.72 a
		November	30.0 b	147 a
		Total	163 b	352 a

[†] Means (n = 24) within the same sampling period (row) with similar letter are not different at 5% significance level by Tukey test.

The greater plant Al concentrations observed in WTR- treated plots than in untreated plots in the 2003 cropping season (Table 4-8) could have resulted from contamination by the surface applied WTR adhering to harvested bahiagrass. The impact of the contaminated pasture on grazing animals is still being investigated. The contamination makes the 2003 data unsuitable (rather 2004 data may be more suitable) to validate the impact of Al-WTR on plant Al concentrations.

Similar to the observations in the glasshouse, the plant Al concentrations from the 2004 cuttings were similar in treatments with and without WTR. November plant samples show greater Al concentrations in WTR-amended than in unamended soils, likely due to cross contamination of treatments induced by the hurricane activities. The similar plant Al concentrations in WTR-treated and untreated treatments is expected because insoluble Al oxides (Al-WTR) are not expected to release toxic Al concentrations or to produce acidity in soils or aqueous systems with pH above 5.2 (Peters and Basta, 1996; Codling et al 2002).

Summary and Conclusions

Results of the field study are consistent with most findings from the glasshouse study. Reductions in soil Total P concentrations with time in soils treated with different P-sources were observed, especially in N-based treatments when no WTR was added, and suggest that substantial soil P losses occurred. In presence of WTR, soil DPS values were reduced, SPSC values increased, and soil soluble P measures (WEP and ISP) as well as P loss potential were reduced. Thus, similar to the results from the glasshouse study, the field data suggest that the added WTR reduced the environmental P hazards associated with the excess P supplied into the soil especially at N-based rates of P-sources. The reduced soil soluble P values (WEP and ISP) were not reflected in reduced yields during the two growing seasons. Yield-weighted P concentrations were reduced in WTR-amended treatments, but plant growth was not. Also, plant Al concentrations were similar in WTR-treated and untreated soils. Thus, amending soils, especially Florida sands, with WTR could be a best management practice (BMP) to reduce the hazards associated with excess P from mineral and organic sources of P land-applied at high rate such (N-based) without fear of reduction in plant yields or Al phytotoxicity.

The organic sources of P varied in RPP values in the field in a similar manner as the values observed in the glasshouse study. The field study RPP values of the Pompano biosolids and poultry manure agreed with the expected moderate phytoavailable biosolids class determined in the glasshouse study, and the Boca Raton biosolids RPP values from both studies were classified as high. Properties identified to affect the RPP values of biosolids are Total P concentration, NaOH- P and %solids. These properties could be the focus of further study into estimating RPP values.

CHAPTER 5
EVALUATION OF SOIL TEST METHODS FOR FLORIDA SANDS TREATED WITH VARIOUS P-SOURCES AND WATER TREATMENT RESIDUAL (WTR)

Introduction

Amorphous, hydrous oxide-rich water treatment residuals (WTR) can control excessive soluble P in coarse-textured low sorbing coastal soils, like the abundant Florida sands. Studies have shown that various types of WTRs can be effective soil amendments in Florida soils (Brown and Sartain, 2000; O'Connor and Elliott, 2001; O'Connor et al., 2002a).

Changes in basic soil properties that can affect P availability to plants by land applying WTR, demand evaluating the suitability of soil test methods for assessing plant available P, and plant response (Basta et al., 2000). A good agronomic soil test method extracts a soil nutrient pool that is representative of that available to plants and that is well correlated with the plant nutrient uptake and other plant growth responses. Soil test methods for P (STP) were developed based on expected P forms in the soils. In most soils, P is associated with either Al, Fe in acid to neutral soils (pH < 7) and with Ca in calcareous soils (Hedley and McLaughlin, 2005). Other factors that determine the degree to which P is bound in a soil include the types of Fe, Al, or Ca compounds (amorphous or crystalline), amounts of P present in the soil, and soil properties, e.g., organic matter content, mineralogy, and pH. Thus, a STP method for a particular region is determined by the predominant soil P sorption processes expected, as affected by regional soil physical and chemical characteristics. The acidic extractant, Mehlich-1 (M-1P) soil test is used extensively in the Southern and Mid-Atlantic States due to the predominance of acidic, highly weathered, low CEC soils in the region. The interpretations of the STP vary with soil properties. For example, Mehlich 1P (M-1P) values of 20-25 mg P kg^{-1} are considered optimum for plant growth in sandy soils, but 10 mg P kg^{-1} is considered adequate for plants in fine-textured soils

(Kamprath and Watson, 1980). In Florida, M-1P values < 15 mg kg^{-1} are regarded as low, > 30 mg kg^{-1} is considered high, and values > 60 mg kg^{-1} are considered very high, from an agronomic standpoint (Kidder et al., 2002).

Various reports have indicated the inadequacy of traditional soil test P methods as measures of plant response to P in WTR-amended soils (O'Connor et al., 2002; Basta et al., 2000). Basta et al. (2000) evaluated three Al-WTRs as soil substitutes and the ability of soil tests to predict P adequacy for Bermudagrass (c*ynodon)*. They found no yield or tissue P response, even though both M3-P and Olsen P predicted P responses. The acidic extractant (M3-P), overestimated plant available P in WTRs by dissolving P sorbed by amorphous Al. Water extractable P (WEP), which accesses the most labile forms of soil P, was suggested as predictor of plant available P in WTR (Basta et al., 2000). Both water-soluble P and Olsen P were reported useful to predict the ability of WTRs to support plant growth, but not P adequacy. Cox et al. (1997) conducted a greenhouse study to determine Al-WTR effects on inorganic forms of P, and availability to wheat (*Triticum aestivum* L.) in a thermic Aquic Hapludult. Of the inorganic P fractions studied, loosely-bound (1 M NH_4Cl-extractable) P was a better predictor of plant P availability in Al-WTR amended soil than M-1P.

Another method which could assess plant available P in WTR amended soils is the iron oxide filter paper method, sometimes referred to as iron strip P (ISP) or the "Pi soil test" (Sharpley, 1991; Sharpley, 1993a, b; Chardon et al., 1996; Pote et al., 1996; Menon et al., 1997). In principle, the Fe-oxide strip acts as an "infinite sink" for desorbable soil P and measures the potential of a soil to continue to release P to plants. The ISP differs from other soil tests that chemically extract P from soils. The Fe oxide coated filter paper strip sorbs P from solution, facilitating desorption of readily available P from soil colloids. Sharpley (1993b) reported ISP was a good indicator of biological availability of P in runoff waters to algae.

A greenhouse study conducted by O'Connor et al. (2002b) suggested water extractable P (WEP) as a potential soil test method for labile P in WTR-amended soils, where Mehlich 1 (M-1P) failed. Fertilizer P requirements can differ in WTR-amended and unamended soil, so careful selection of soil testing methodology is necessary. The suitability of various soil tests is expected to depend on soil, soil reactions, and P forms, but could be even more complex when WTR is co-applied with different P-sources. We hypothesized that there exist a suitable agronomic soil test method for P in Florida soils amended with various sources of P and WTR. Accordingly, the main objective of this study was to identify a suitable soil test method for P bioavailability in Florida soils amended with different P-sources and WTR.

Materials and Methods

Data from the glasshouse (Chapter 3) and the field study (Chapter 4) were used to evaluate the suitability of soil test P (STP) methods as predictors of plant response in Florida sands.

Glasshouse Experiment

The experiment involved continuous growing of pasture grasses (bahiagrass (*paspalum notatum* Fluggae), ryegrass (*Lolium perenne* L.), and second bahiagrass crop) in succession. Crops were grown in a Florida sand amended with four P-sources at two P-source rates, and three rates of WTR. Details of the experimental procedures are given in Chapter 3. The soil samples taken following harvest of each grass were analyzed for varying measures of plant available P (M-1P, WEP and ISP). In addition, time zero soil samples were analyzed for ammonium acetate (pH 4.8) extractable P (AA-P) to check for its possible improvements over other STP methods. The AA-P method involves extracting soil samples with a mixture of 0.7N NH_4OAc and 0.5N CH_3COOH solution at 1:5, soil:solution ratio. The mixtures were shaken for 30 minutes, centrifuged, and filtered (0.45µm) before analysis (Page et al., 1965, Sartain, 1979). Table 5-1 summarizes the methods used for the soil analysis, and details of the analysis procedures are explained in Chapters 2 and 3. The plant dry matter yields were determined and samples were analyzed for P concentration (Chapter 3). Phosphorus uptake was calculated as the product of DM and P concentrations for each harvest, and yield-weighted P concentrations obtained by dividing the total P uptake by the total dry matter weight.

Table 5-1. Summary of phosphorus extraction procedures used

Method	Extractant	Soil:Solution ratio	Shaking time	Reference
Water extractable P (WEP)	Distilled water	1:10	60 min.	Sharpley and Moyer, 2000
Mehlich 1 P (M-1P)	0.05M HCl + 0.0125M H_2SO_4	1:4	5 min.	Sims, 2000
Iron strip P (ISP)	FeO paper + 0.01M $CaCl_2$	1:40	16 h	Chardon et al., 1996
Ammonium acetate P (AA-P)	0.7M NH_4OAc + 0.5M CH_3COOH	1:5	30 min.	Sartain, 1979; Page et al.,1965

Field Experiment

Data from the field experiment (Chapter 4) were used to validate the glasshouse experiments, and provided additional data for the soil test validation effort. The dry matter yields, P concentrations, and P uptake of the test plant (established bahiagrass) were determined from the harvests of the 2003 and 2004 growing seasons. Soils sampled from the A (0-5cm) in June 2003 and in January 2004 served as measures of soil P for the 2003 and 2004 growing seasons. Additional soil samples (0-15 cm) were taken in March 2004 to better account for A horizon contribution to P supply, and were also related to plant parameters of the 2004 growing season. All soil samples were analyzed for WEP, ISP, and M-1P. Details of the experimental procedures and analysis are provided in Chapters 4 and 2.

Statistical Analysis

Normal probability plots and residuals of the data were studied to ensure the samples satisfied the assumptions of normality, constant variance, and independence. Pearson's correlation and regression analysis between soil extractable P values and plant responses, and other statistical tests, were done using SAS (SAS Institute, 1999). Graphical representations were done using Excel software.

Results and Discussion

Soil Test P and WTR Treatments

Generally, the extractable P values (WEP, ISP and M-1P) for the same soil samples differed. The greatest values were observed as M-1P and the least as WEP. Apart from the control treatment, M-1P values at time zero of first bahiagrass crop exceeded 15 mg kg^{-1}, indicating sufficient soil P for plant growth in all the treatments (Kidder et al., 2002). Thus, the growth (DM yield) response of the first bahiagrass cropping was expected to be unaffected if the plants could assess the same soil P pool as M-1P, including some of the WTR-sorbed P. Stanley and Rhoads (2000) reported no first year response of bahiagrass to P fertilization if the M-1P values exceed 16 mg kg^{-1}, and 39 mg kg^{-1} initial STP was shown sufficient for two years growth. A better response was expected in the second bahiagrass cropping because soil M-1P values across the treatments at planting of the grass ranged from low (< 15 mg kg^{-1}) to very high (>60 mg kg^{-1}).

Water extractable P, an expected good test of the readily available P, indicated lower P in the soils amended with WTR than in soils without WTR across P-sources throughout the study. The lower soluble P in soils receiving WTR than in those without WTR was confirmed by the low soil ISP values in WTR treatments (Fig. 5-1).

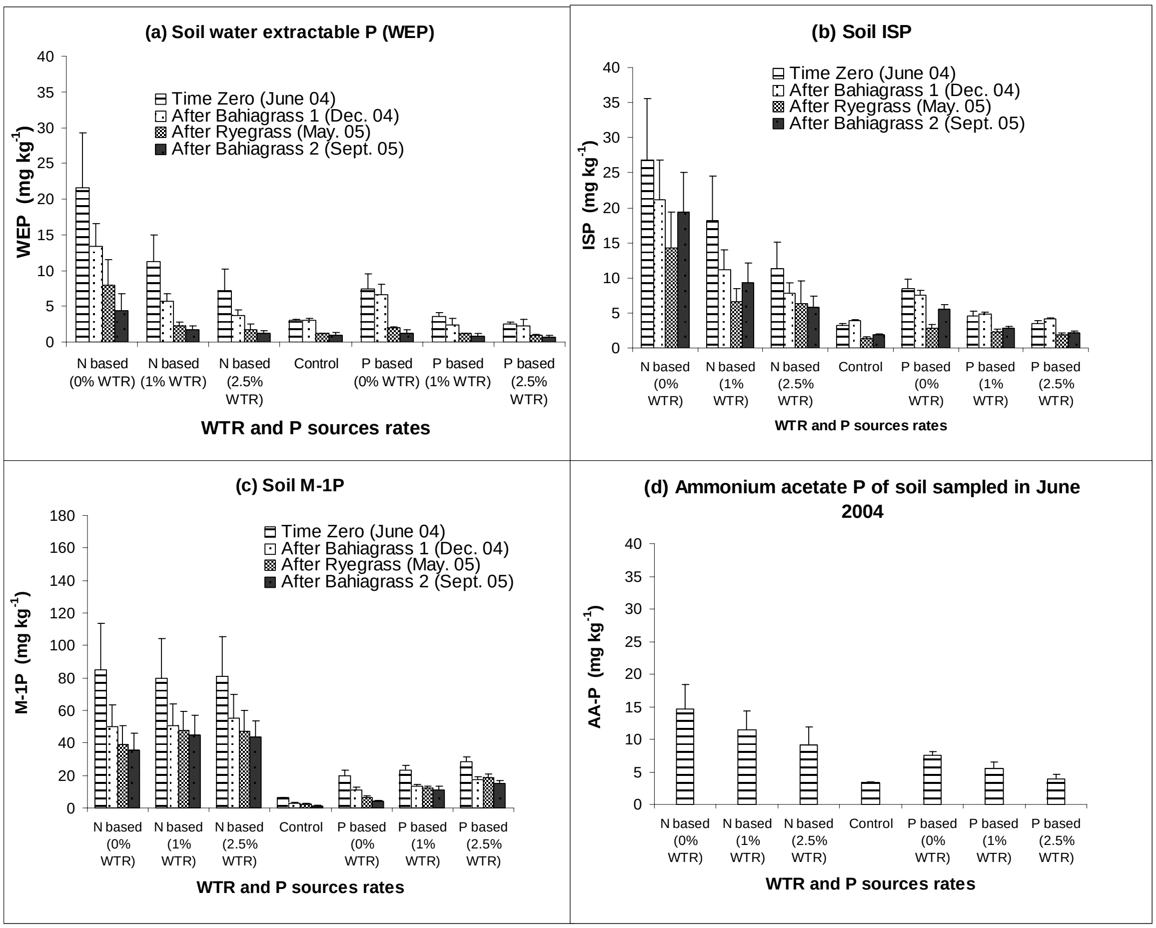


Figure 5-1. Extractable P [(a)water extractable P (WEP), (b) iron strip P (ISP), (c) Mehlich 1 P (M-1P), and (d) ammonium acetate P (AA-P)] values in samples taken during the glasshouse study as affected by application rates of P-sources and water treatment residual (WTR). Note the different scale for M-1P

Both WEP and ISP are measures of soil soluble P (readily available P) and are also regarded as good indices of environmental P hazard (Menon et al., 1997; Pote et al., 1999; Kleinman et al., 2005; Vadas et al., 2006).

The trends in AA-P values for samples taken in June were similar to trends in WEP and ISP values (Fig. 5-1). The greater, or similar, M-1P values for treatments with increasing amounts of WTR at each rate of the P-sources (Table 5-2 and Fig. 5-1d) indicate that the acidic M 1-P extractant (pH<2) releases some of the P sorbed by the WTR.

The trends of pooled data (samples taken throughout the glasshouse study) of the various STP methods are shown in Fig. 5-2. Both WEP and ISP values reflected the effects of WTR, and the trend of extractable P for both measures of P was: 0% WTR > 1% WTR > 2.5% WTR (Fig. 5-2a). Unlike soil WEP and ISP values, the effects of WTR treatments could not be distinguished by M-1P (Figs. 5-2b and 5-2d).

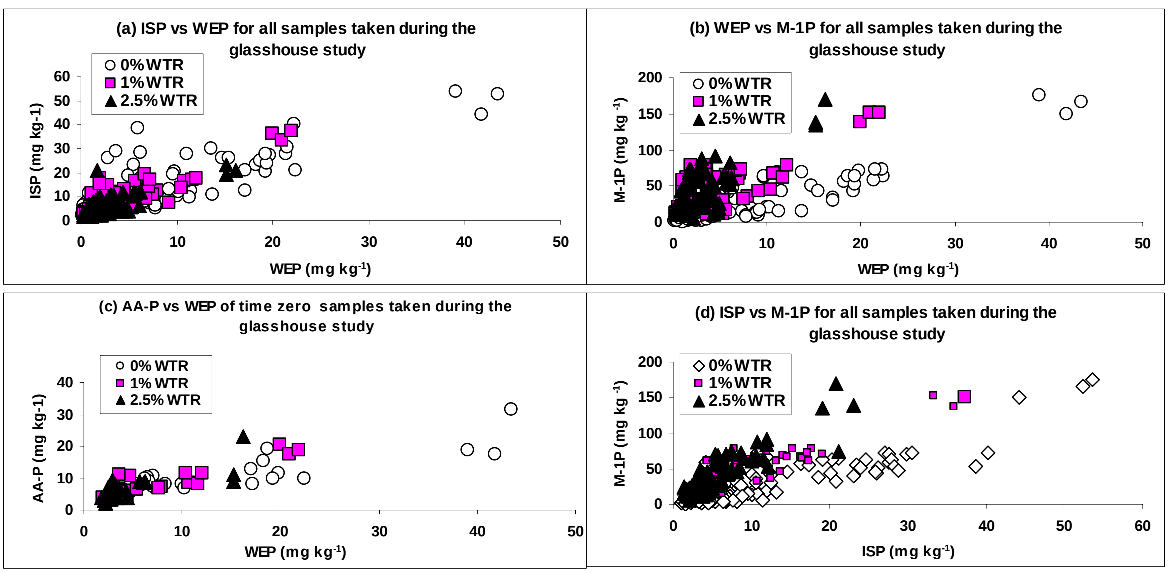


Figure 5-2. Relationships between water extractable P (WEP) and (a) iron strip P (ISP), (b) Mehlich 1 P (M-1P), (c) ammonium acetate P (AA-P) and (d) between M-1P and ISP values of samples taken during the glasshouse study and the effects of water treatment residual (WTR).

The AA-P tested on time zero soils improved identification of the WTR treatments (Figs. 5-1c and 5-2c), but was not better than WEP or ISP.

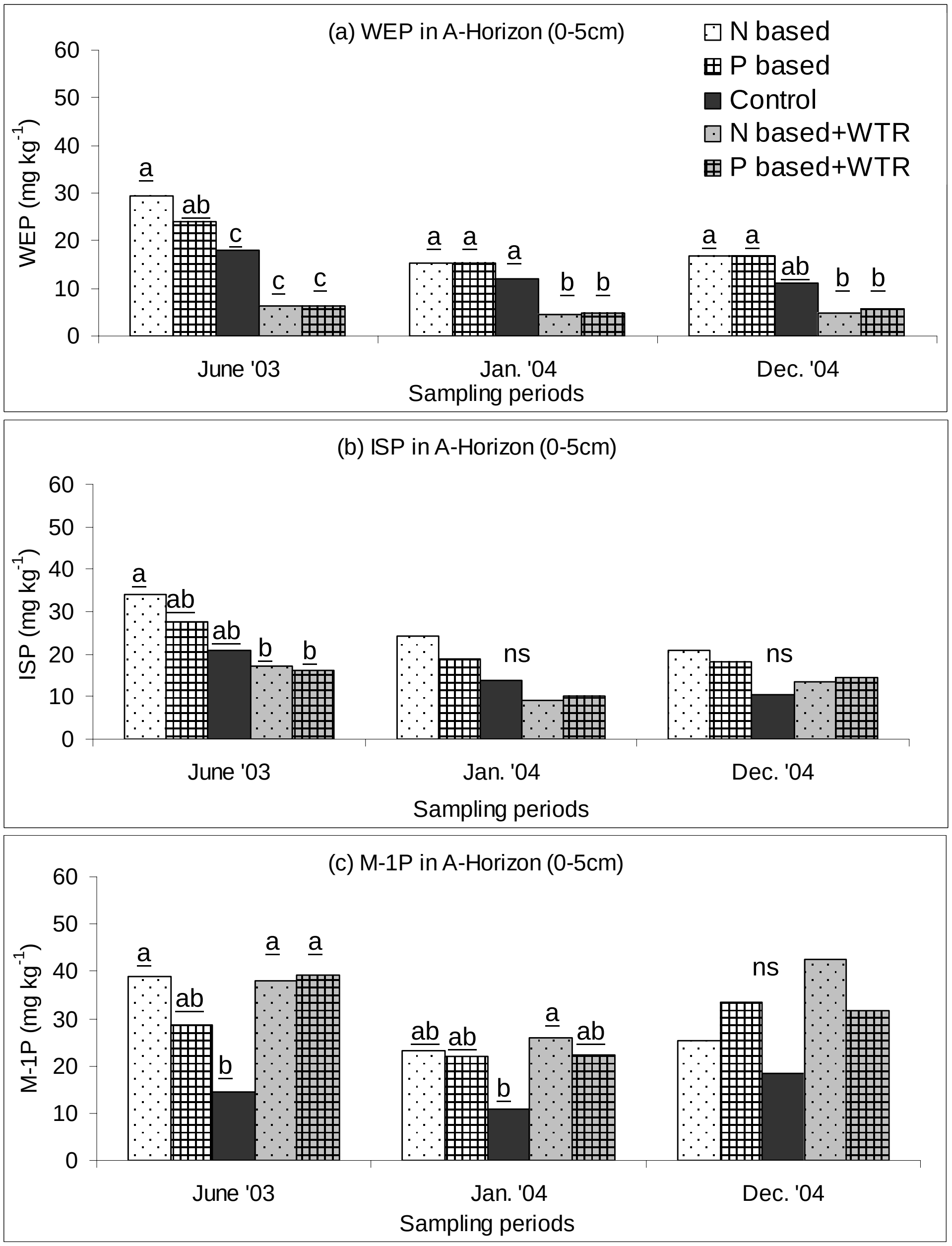


Figure 5-3. Effects of P-source rates and water treatment residual (WTR) on (a) water extractable P (WEP), (b) Iron strip P (ISP), and (c) Mehlich 1P (M-1P) values of A-horizon (0-5cm) soil samples taken during the field study.

Data from the field experiment exhibited trends similar to those observed in the glasshouse. The soluble P measures, especially WEP values were greater in the absence of, than in the presence of, WTR (Fig. 5-3). Similar, or greater, M-1P values were observed in treatments with or without WTR for each application rate in A-horizon (0-5cm) samples taken during the study. Thus, as observed in the glasshouse study, M-1P could not distinguish between WTR treated and untreated soils in the field. Data from both the glasshouse and field experiments suggest WEP and ISP as good measures of soil soluble P in WTR-treated soils, and both were better than the traditional agronomic STP (M-1P).

Soil Test P and Plant Response

The suitability of an agronomic soil test method is judged by the degree of relationship between extractable nutrient values and plant responses. Thus, the suitability of soil test extractant could be established by the correlation and regression relationships between the STP measured and plant responses such as DM, P concentrations, and P uptake.

Generally, low correlation coefficients of plant yields with the varying measures of soil P values were observed. Sufficient plant available P, especially in the first bahiagrass cropping probably contributed to the muted responses observed, as yield was not limited by the soil P in most treatments. The plant tissue concentrations also indicated sufficient P available for plant growth, even in the ryegrass (second) cropping. The P concentrations in all of the treatments exceeded 1.0 g kg^{-1} recommended for ryegrass by Hylton et al. (1965). The soil P values correlated better with plant P concentrations and P uptake than with dry matter yields (Table 5-3). Both WEP and ISP measures correlated better with the first bahiagrass crop responses than did M-1P values (Table 5-2). However, M-1P correlated better with the ryegrass and the second bahiagrass cropping responses, than with first bahiagrass parameters. Also, the correlation of M-1P values with P concentrations and P uptake compared favorably well with WEP and ISP values after the first bahiagrass cropping. The ammonium acetate P at time zero did not improve the correlation of WEP and ISP values with first bahiagrass crop response, but the combined values correlated better than M-1P (Table 5-2).

Table 5-2. Correlations between varying measures of soil test P and plant parameters in the glasshouse study

Plant	Dependent variable	Soil P			
		§WEP	¶ISP	††M-1P	Ammonium Acetate P
Bahiagrass (First)	Dry Matter	0.413† 0.0002‡	0.394 0.0005	0.377 0.0008	0.359 0.0016
	P concentration	0.860 <.0001	0.801 <.0001	0.561 <.0001	0.722 <.0001
	P uptake	0.849 <.0001	0.797 <.0001	0.596 <.0001	0.700 <.0001
Ryegrass	Dry Matter	0.333 0.0035	0.574 <.0001	0.845 <.0001	-
	P concentration	0.772 <.0001	0.821 <.0001	0.556 <.0001	-
	P uptake	0.725 <.0001	0.857 <.0001	0.718 <.0001	-
Bahiagrass (Second)	Dry Matter	0.526 <.0001	0.669 <.0001	0.716 <.0001	-
	P concentration	0.595 <.0001	0.596 <.0001	0.585 <.0001	-
	P uptake	0.669 <.0001	0.723 <.0001	0.701 <.0001	-

†Correlation coefficient (r)
‡*p*-value
§Water extractable P
¶Iron strip P
††Mehlich 1P

Table 5-3. Coefficients of determination (r^2) and other regression parameters obtained by relating various soil test P values against plant data from the glasshouse study

Plant	Dependent variable	Independent variable	r^2	CV	*p*-values
Bahiagrass (First)	†Dry matter	‡WEP	0.18	17	0.0008
		§ISP	0.18	17	0.0007
		††AA-P	0.21	17	0.002
		¶M-1P	0.13	18	0.007
	P concentration	WEP	0.74	30	<0.0001
		ISP	0.64	35	<0.0001
		AA-P	0.52	41	<0.0001
		M-1P	0.32	49	<0.0001
	P uptake	WEP	0.72	41	<0.0001
		ISP	0.64	47	<0.0001
		AA-P	0.49	56	<0.0001
		M-1P	0.36	63	<0.0001
Ryegrass	Dry matter	WEP	0.14	16	0.0038
		ISP	0.48	12	<0.0001
		M-1P	0.72	9	<0.0001
	P concentration	WEP	0.6	25	<0.0001
		ISP	0.67	23	<0.0001
		M-1P	0.31	33	<0.0001
	P uptake	WEP	0.53	35	<0.0001
		ISP	0.73	26	<0.0001
		M-1P	0.52	35	<0.0001
Bahiagrass (Second)	Dry matter	WEP	0.32	22	<0.0001
		ISP	0.57	18	<0.0001
		M-1P	0.57	18	<0.0001
	P concentration	WEP	0.35	23	<0.0001
		ISP	0.36	23	<0.0001
		M-1P	0.34	23	<0.0001
	P uptake	WEP	0.45	40	<0.0001
		ISP	0.52	38	<0.0001
		M-1P	0.49	39	<0.0001
Total	Dry matter	WEP	0.38	12	<0.0001
		ISP	0.50	11	<0.0001
		AA-P	0.50	11	<0.0001
		M-1P	0.51	11	<0.0001
	P concentration	WEP	0.81	20	<0.0001
		ISP	0.69	25	<0.0001
		AA-P	0.51	32	<0.0001
		M-1P	0.24	40	<0.0001
	P uptake	WEP	0.82	26	<0.0001
		ISP	0.75	31	<0.0001
		AA-P	0.58	40	<0.0001
		M-1P	0.34	50	<0.0001

†Quadratic model was used for plant dry matter yields, while simple linear regression were used for P concentrations and P uptake
‡Water extractable P; §Iron strip P; ¶Mehlich 1P; ††Ammonium acetate P

At initial planting, treatments effects were likely minimal, but the proportions of soil P extracted by both WEP and ISP still related well with plant available P, whereas M-1P failed. The coefficients of determination obtained from regressions of plant dry matter yields, P concentrations and P uptakes with varying measure of STP also showed that the WEP and ISP value predictabilities were better than M-1P values, especially in first bahiagrass cropping (Table 5-3). However, with time, the regressions with M-1P values improved. Soil M-1P may be inadequate to assess plant response to P in soils newly treated with WTR, whereas the WEP or ISP soil tests are better. However, with time (>5 months), the predictability of plant responses by M-1P improved (Table 5-3). The glasshouse study by Cox et al. (1997) also reported M-1P as a good indicator of P availability to wheat (*Triticum aestivum* L.) in WTR-treated soils. Cox et al. (1997) did not evaluate the WEP and ISP methods.

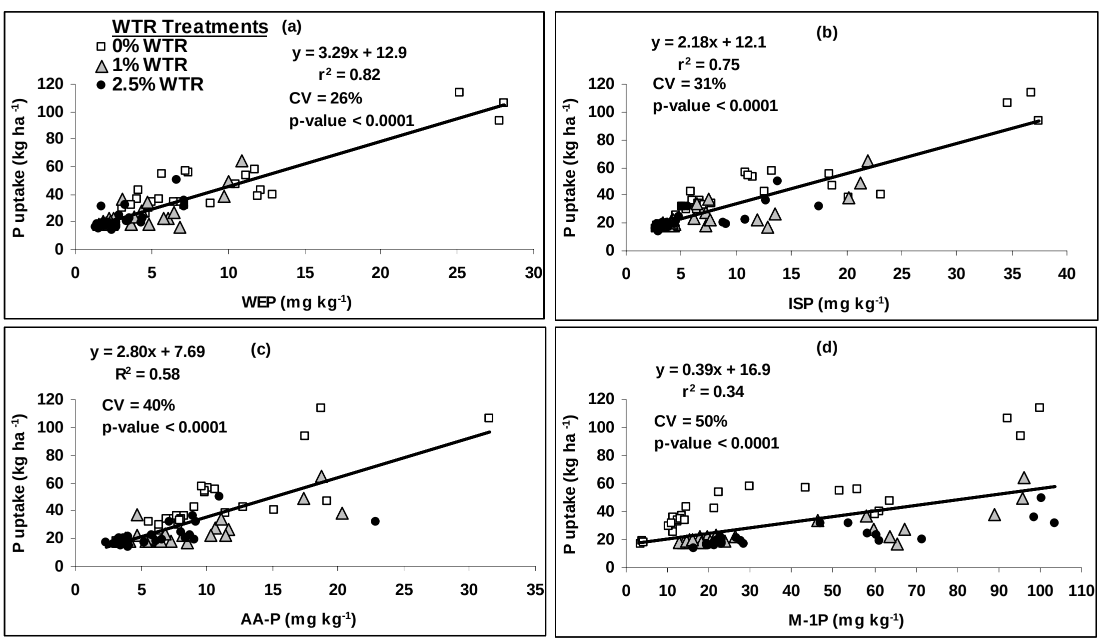


Figure 5-4. Regression of total P uptake (sum for the three croppings) and average (a) water extractable P (WEP), (b) iron strip P (ISP), (c) ammonium acetate P (AA-P), and (d) Mehlich 1 P (M-1P) values of soil samples at planting of the grasses.

Regression of total P uptake (sum of P uptake for the three croppings) with averages of STP values at planting of the three grasses established WEP ($r^2 = 0.82$) as a good predictor of plant response in WTR-amended soils (Fig. 5-4). The ISP method ($r^2 = 0.75$) was also successful, whereas M-1P failed. The WEP and ISP values could be used interchangeably, as both were closely related ($r^2 = 0.65 – 0.93$) with each other throughout the study (Table 5-4 and Fig. 5-5).

Table 5-4. Coefficients of determination (r^2) and other regression parameters obtained by plotting various soil test P values against each other (glasshouse study).

Dependent variable	Dependent variable	Independent variable	Intercept	Slope	r^2	CV	*p*-values
At planting of first bahiagrass crop	[§]ISP	[‡]WEP	1.16	1.22	0.93	26	<0.0001
	[†]M-1P	WEP	19.3	3.64	0.57	55	<0.0001
	M-1P	ISP	13.1	3.22	0.72	45	<0.0001
	M-1P	[¶]AA-P	- 4.88	6.59	0.66	50	<0.0001
	WEP	AA-P	- 3.23	1.41	0.70	57	<0.0001
	ISP	AA-P	- 4.20	1.89	0.78	45	<0.0001
At planting of ryegrass crop	ISP	WEP	2.02	1.29	0.67	46	<0.0001
	M-1P	WEP	20.6	2.01	0.13	75	<0.0001
	M-1P	ISP	9.75	2.35	0.47	59	<0.0001
At planting of second bahiagrass crop	ISP	WEP	1.95	1.47	0.65	65	<0.0001
	M-1P	WEP	21.2	2.42	0.14	75	<0.0001
	M-1P	ISP	15.8	2.04	0.33	66	<0.0001

[†]Mehlich 1P
[‡]Water extractable P
[§]Iron strip P
[¶]Ammonium acetate P

The greater suitability of WEP and ISP as agronomic soil tests for P than M-1P was demonstrated in the greater correlation coefficient (r) for WEP and ISP values than for M-1P in the field study (Table 5-5). Overall, the correlation coefficients were small ($r < 0.7$) because of the less impact of the treatments on the plant responses. The established, deep-rooted bahiagrass accessed nutrients in the lower E and Bh horizons (which were not affected by the treatments), in addition to those in the A-horizon (Ibrikci et al., 1994). This phenomenon has made identifying a suitable soil test method to predict bahiagrass response to P unsuccessful (Ibrikci et al., 1992, Rechcigl et al., 1992), and soil testing (M 1-P) is not recommended for bahiagrass pastures in central and south Florida (Kidder et al., 2002).

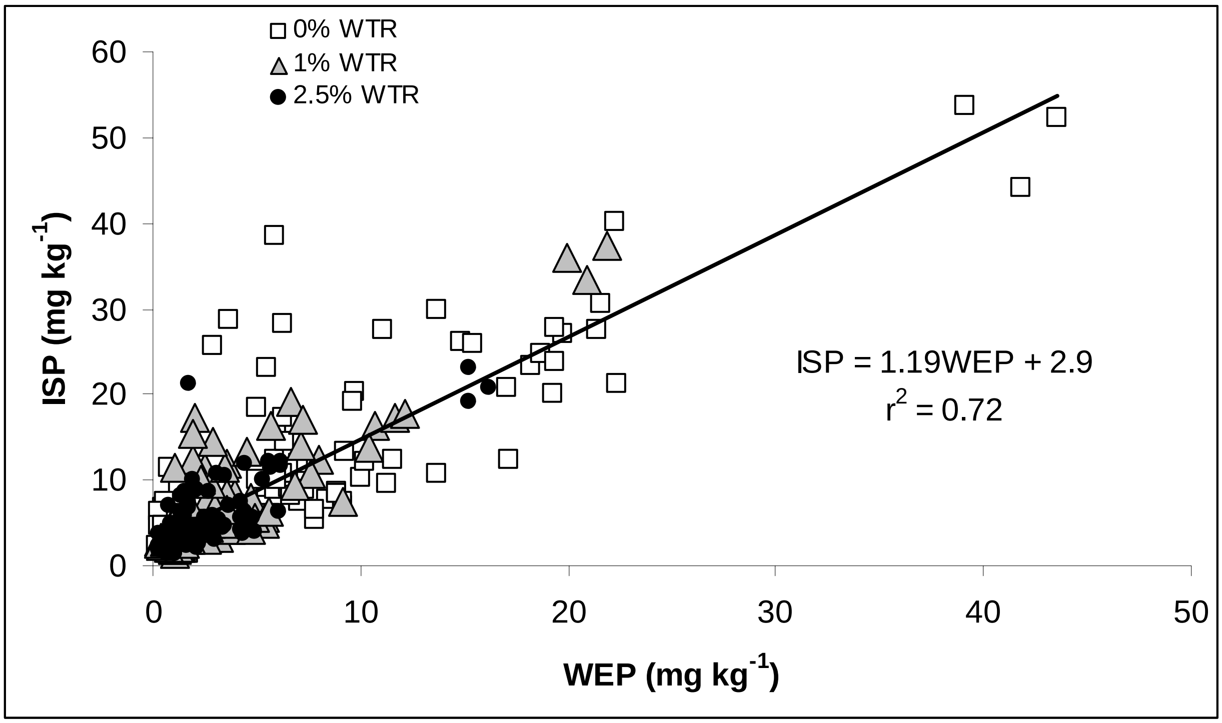


Figure 5-5. Regression of water extractable P (WEP) and iron strip P (ISP) values of soils sampled at planting of the three croppings..

Irrespective of the smaller correlation coefficients, values of WEP and ISP correlated (P <0.05) with plant P uptake and P concentration throughout the study, even when M-1P did not (Table 5-5). Thus, the field data support the observations from the glasshouse study that both WEP and ISP could be used in WTR-amended soil as soil tests, whereas M-1P fails.

The field study also confirmed that WEP and ISP methods clearly separate the WTR-treated and untreated soils, but M-1P does not (Fig. 5-6).

Table 5-5. Pearson's correlation coefficients between the different measures of soil test P of A-horizon soils (0-5cm) and plant data for 2003 and 2004 (field study).

Plants Data	June 2003 soil P and 2003 plant data			Jan. 2004 Soil P and 2004 plant data		
	[§]WEP	[¶]ISP	[††]M-1P	WEP	ISP	M-1P
Dry matter	0.216[†]	0.249	0.024	0.173	0.146	0.117
	0.1279[‡]	0.0777	0.8621	0.2243	0.3063	0.4098
P uptake	0.448	0.420	0.068	0.623	0.286	0.102
	0.001	0.0021	0.6339	<.0001	0.0416	0.4733
P concentration	0.581	0.483	0.086	0.647	0.261	0.035
	<.0001	0.0003	0.5484	<.0001	0.0636	0.8069

[†] Correlation coefficient (r) [‡] *p*-value [§] Water extractable P [¶]Iron strip P [††] Mehlich 1P

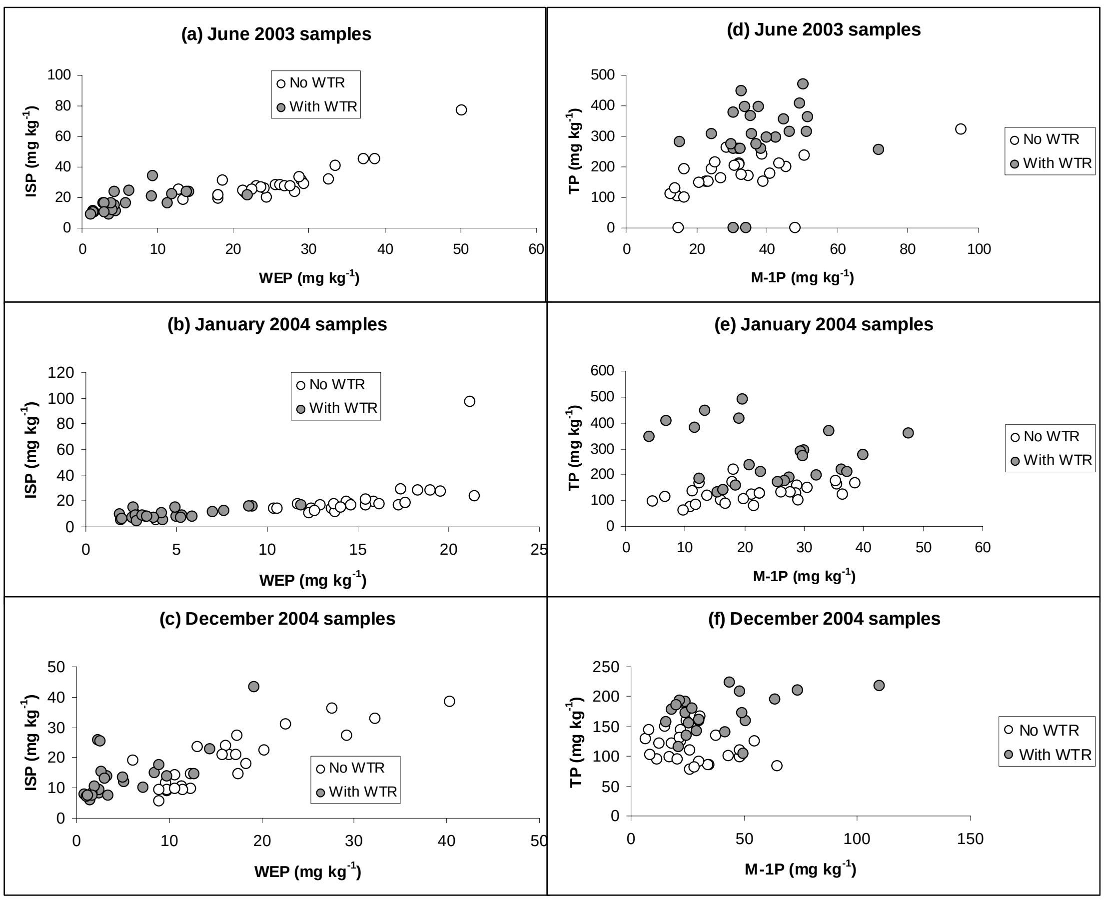


Figure 5-6. Relationships between water extractable P (WEP) and iron strip P (ISP) of (a) June 2003, (b) January 2004, (c) December 2004; and between Mehlich 1 P (M-1P) and Total P (TP) values of (d) June 2003, (e) January 2004, (f) December 2004 soil samples taken during the field study and the effects of water treatment residual (WTR)

The WEP and ISP methods better related with each other than with M-1P values (Table 5-6). Thus, the two soil test P (WEP and ISP) can be used interchangeably. Soil WEP determination is easier and simpler than ISP. The good relationship found between the two STP methods indicates a good estimate of the ISP (bioavailable P) could be achieved from the simpler WEP values in WTR-amended soil.

Table 5-6. Coefficients of determination (r^2) values obtained between varying soil test P measures for the two planting seasons during the field study.

Soil Tests	Depth	Slope	Intercept	r^2
†M-1P vs. §ISP (All)	0-5cm and 0-15cm	0.24	28.2	0.02
M-1P vs. ‡WEP (All)	0-5cm and 0-15cm	-0.05	32.9	<0.01
ISP vs. WEP (All)	0-5cm and 0-15cm	0.97	5.43	0.58
ISP vs. WEP (June 2003)	0-5cm	0.82	10.0	0.72
ISP vs. WEP (Jan 2004)	0-5cm	1.37	1.79	0.39
ISP vs. WEP (Dec 2004)	0-5cm	0.78	7.82	0.56
ISP vs. WEP (March 2004)	0-15cm	0.83	4.08	0.78
ISP vs. WEP (Dec 2004)	0-15cm	1.09	3.93	0.57

†Mehlich 1P
‡Water extractable P
§Iron strip P

Summary and Conclusions

Strongly acidic extractants, including M-1P, are not suitable as measures of plant response to P in WTR-amended soils. Both water extractable P (WEP) and Iron strip P (ISP) methods applied to soils sampled at planting of bahiagrass (*paspalum notatum* Fluggae*)*, ryegrass (*Lolium perenne* L.), and a second bahiagrass crop distinguished the treatments into WTR-treated and untreated soils. Correlations of the dry matter yields, P concentrations, and P uptake of the first bahiagrass crop were also better with WEP and ISP values than with M-1P values, but regression of plant responses with M-1P improved after the first cropping. Total plant P uptake correlated better with WEP ($r^2 = 0.82^{***}$) and ISP ($r^2 = 0.75^{***}$) than with M–1P ($r^2 = 0.34^{***}$).

Data from the field study also support WEP and ISP as better STP methods than M-1P in WTR-treated soils. Both WEP and ISP are recommended as STP methods for Florida soils treated with WTR.

CHAPTER 6
APPLICATION RATE OF WATER TREATMENT RESIDUAL (WTR) FOR AGRONOMIC AND ENVIRONMENTAL BENEFITS

Introduction

Land application of Al water treatment residual (Al-WTRs) can serve as a best management practice (BMP) to reduce environmental hazards associated with excessive soil phosphorus (P) loads. The Al-WTR can increase soil P retention and, thereby, decrease offsite P loss to water bodies (O'Connor et al., 2002a; Dayton et al., 2003; Novak and Watts, 2004). However, over application of the residuals can lead to excessive immobilization of soil P and induce plant P deficiencies. Thus, knowing the correct amount of WTR to land apply is critical.

Determining the appropriate application rates of WTR is complicated by variations in chemical properties of the residuals as influenced by the source of water, treatment chemicals and processings used by treatment plants (O'Connor et al., 2004). The WTRs not only vary in total Al concentrations, but also other chemical properties that affect the sorption capacity, including other elemental concentrations (e.g., Fe and P) and metal oxides forms (amorphous and crystalline). The WTRs used in a recent study by Makris (2004) had Al concentrations that ranged between 37 and 103 g kg^{-1} for Al-WTRs and between 1.5 – 9.8 g kg^{-1} for Fe-WTRs and varying P and Fe concentrations (Table 6-1). Twenty–one Al-WTRs used in a study by Dayton et al. (2003) also widely varied in total Al (14.7 -177 g kg^{-1}), Fe (5.02 – 49.9 g kg^{-1}) and P (0.20 – 4.04 g kg^{-1}) concentrations (Table 6-1).

In a batch equilibration study by Dayton et al. (2003) to examine the components of WTR that could contribute to P sorption properties, oxalate extractable Al (Al_{ox}) correlated with the linearized Langmuir P_{max} values. The sorption capacities of various WTRs were also shown by O'Connor et al. (2002a) to depend on the oxalate extractable Al, Fe, and P concentrations of the

WTRs. Haustein et al. (2000) compared the abilities of two Al rich materials to reduce runoff P from excessively P-impacted fields. Material with greater Al concentration (46.7 g kg^{-1}) applied at both 9 and 18 Mg ha^{-1} decrease runoff P below those of control plots throughout the 4-month experimental periods. However, at the same rates (9 and 18 Mg ha^{-1}), material with lower Al concentration (15.9 g kg^{-1}) decrease the runoff P concentrations for only 1month. Pautler and Sims (2000) reported a significant relationship (r = 0.61, *p*-value = 0.01) between P sorption and amorphous Al and Fe concentrations of soils. Elliott et al. (2002b) suggested that the phosphorus saturation index (PSI) determined from 0.2M oxalate extractable P, Al and Fe concentrations (P_{ox}, Al_{ox} and $Fe_{ox,}$ respectively) was useful for determining WTR application rates. The soils and the P-sources that can be co-applied with WTR can also vary in P_{ox}, Al_{ox} and $Fe_{ox.}$ Thus, the compositional variability of soils, P-sources, and WTRs need to be accounted for in determining the amount of WTR to be applied to a soil.

Table 6-1. Total and oxalate extractable phosphorus, aluminum and iron in water treatment residuals (WTR) used in some recent studies

Study	<-------------Total (g kg^{-1})---------->			<-------------Oxalate (g kg^{-1}) ---------->		
	P	Al	Fe	P	Al	Fe
Makris, 2004	0.80 – 3.1	37.0 - 103	5.70 -20.7	0.50 – 2.98	29.0 – 91.0	2.30 – 5.80
Dayton et al., 2003	-	14.7 - 177	5.02 -49.9	0.30– 5.14	1.33 – 48.7	0.43 – 7.14
O'Connor et. al., 2005	1.91 -2.79	78.1 -145	2.97 -5.33	0.61 -3.02	73.7 -109	0.78 – 3.23

Application rates of WTR used in most studies are often based on arbitrary dry weight amendments:soil ratio, with little account taken of the chemical composition of the materials in arriving at the WTR rates (Peters and Basta, 1996; Basta and Storm, 1997; Gallimore et al., 1999; Ippolito et al., 1999; Brown and Sartain, 2000; Haustein et al., 2000; Codling et al., 2002; Dayton et al., 2003; Novak and Watts, 2004). Application of WTR based on dry weight (or soil:amendment ratio can result in excessive or inadequate immobilization of soil soluble P depending on the amount and reactivity of Al and or Fe added in the WTRs. Based on the consensus among researchers, the STP could be maintained at levels that optimize crop yields and still minimize the risk of offsite P transport (Higg et al., 2000). However, this agro-environmental optimal need to be determined and its suitability as a basis for WTR application rate evaluated.

Potential indices of environmental P losses are the degree of phosphorus saturation (DPS) for soils, and the phosphorus saturation index (PSI) for amendments (P-sources and WTR). Both DPS and PSI are calculated as ratios of P_{ox} to the sum of Al_{ox} and Fe_{ox} of the soil and amendment, respectively, but with α-value (which depends on soil characteristics) included in the denominator for DPS calculation (van der Zee, et al., 1987; Breeuwsma and Silva, 1992; Nair et al., 2004).

A recent study by Nair and Harris (2004) recommended determining the soil phosphorus storage capacity (SPSC) values rather than DPS as an index to predict the amount of P a soil can sorb before exceeding a threshold soil equilibrium concentration. The SPSC values indicate the risk arising from P loadings as well as inherent P sorption capacity of the soil. The SPSC values range from negative values (for highly P-impacted soil) to positive values (for less P-impacted soils). Zero SPSC values represents the value at which the soil PSR is at the threshold value (0.15) related to a soil solution concentration of 0.1 mg L^{-1} (Nair and Harris, 2004).

Application of WTR, if based on SPSC values, could target only the excess P that poses environmental threats and is not expected to negatively impact the P pools needed to meet plant

P requirement. However, there is need to determine the agronomic threshold SPSC value above which plant yields are negatively impacted. The SPSC-based rates of WTR were hypothesized to result in similar soluble P concentrations and plant yields, irrespective of soil P loads and sources of P. Further, it was hypothesized that there exist an SPSC value above which the plant yields are reduced. The objective of this study was to evaluate the impact of SPSC-based Al-WTR application rates on plant yields and P concentrations, and to identify the agro-environmental SPSC threshold.

Materials and Methods

Data from the glasshouse (Chapter 3) and the field experiment (Chapter 4) were used for the study. The SPSC values were calculated from the soil oxalate extractable P, Fe, and Al concentrations as:

$$SPSC = (0.15 - PSR) * (Al_{ox} + Fe_{ox}) \qquad \text{Equation (6-1)}$$

$$PSR = P \text{ saturation ratio} = (P_{ox})/(Al_{ox} + Fe_{ox}) \qquad \text{Equation (6-2)}$$

Where P_{ox}, Al_{ox}, and Fe_{ox} are 0.2M oxalate extractable P, Al, and Fe concentrations of the soil expressed in mmoles, respectively.

The 0.15 value used in the SPSC calculation was the threshold PSR value suggested by Nair and Harris (2004) for Florida soils. The index, SPSC, was expressed as equivalent mg P kg^{-1} by multiplying the SPSC value calculated in Equation 6-1 by 31 (the atomic mass of P) as:

$$SPSC\ (mg\ P\ kg^{-1}) = (0.15 - PSR) * (Al_{ox} + Fe_{ox}) * 31 \qquad \text{Equation (6-3)}$$

The relationship between the soil WEP and SPSC values was used to determine the environmental thresholds, while critical plant P concentrations were identified using Cate-Nelson method (Cate and Nelson, 1971).

Results and Discussion

Soil Phosphorus Storage Capacity (SPSC) in the Glasshouse Study

The soil samples taken at time zero of first bahiagrass are expected to give a better picture of how the SPSC values are affected by the treatments, as the samples are not affected by the uptake by previous crops. For all P-sources, at both application rates, SPSC values increased with increasing WTR rates due to the added Al (Fig. 6-1). The SPSC values were lower at the high P application rate (N-based rate) reflecting greater P:Al+Fe ratio than at the low rate (P-based rate). The greater added P at N-based rates obviously provided (saturated the P sorption sites) more excess P than in P-based rates. The SPSC values at higher P loads (N-based rate) were negative for the four P-sources in the absence of WTR, which indicates P added exceeded soil P storage capacity. This establishes the N-based rates of the P-sources as not environmentally friendly without WTR.

The variation in the magnitude of the SPSC values at P-based rates (where equal P loads was applied) without WTR, reflects the differences in the P-source chemical compositions (especially Al, Fe, and P, as summarized by PSI). The differences in the SPSC values suggest soils amended with P-sources of different PSI values will need different amounts of Al and or Fe added as WTR to achieve equal soil SPSC values.

Addition of WTR increases the P storage capacity at either P-based or N-based rates. However, SPSC values were greater at the P-based, than at the N-based, rates when an equal amount of WTR is applied for each P-source. Applying equal amounts of WTR also gave different SPSC values for different P-sources at either the P- or N-based rates. Thus, varying amounts of WTR will be needed depending on the source PSI to achieve equal SPSC value for soils treated with various P-sources. The variations of SPSC values for different P-sources at each application rate and WTR indicate effects of the P, Al and Fe composition (which vary for different P-sources) on the soil. The variations could be accounted for by applying P-sources and WTR based on the desired SPSC value.

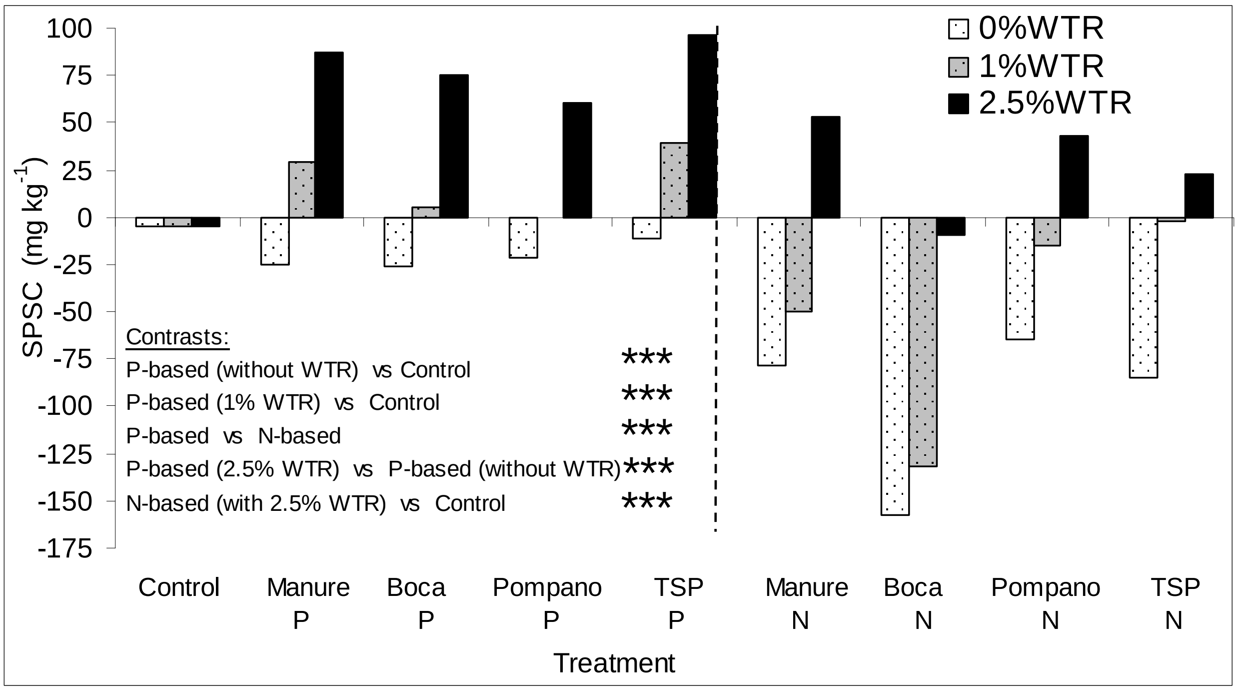


Figure 6-1. Soil phosphorus storage capacity (SPSC, mg kg^{-1}) values for the different treatments in time zero samples taking during glasshouse study. (Treatments ending in P, and N, are P-based and N-based rates of the sources, respectively).

Values of SPSC increased with WTR addition in all samples taken during the study due to reduction in soil P:Al+Fe ratio (or PSR)(Fig. 6-2). The SPSC values at the P-based rate without WTR were close to 0 mg P kg^{-1}, confirming the rate (P-based) as environmentally friendly. Zero SPSC value is equivalent to PSR value of 0.15, which is the environmental threshold. However, the N-based rates without WTR resulted in negative SPSC values even at 1% WTR and, in some cases, at 2.5%WTR. Obviously, the SPSC values at the two rates increased with increasing WTR rates.

The negative values of SPSC at the N-based rates of P-sources indicate that soil is receiving excess P, and agrees with other studies that N-based rates load soil with excess P that could cause negative environmental impact (Reddy et al., 1980; Pierzynski, 1994; Peterson et al., 1994; Maguire et al., 2000). However, with addition of WTR, the SPSC values of the N-based rates were increased and even become positive for some P-sources at 2.5% WTR (Fig. 6-1 and 6-2). The applied WTR obviously creates P sorption sites for the soil soluble P in excess of P-based rates.

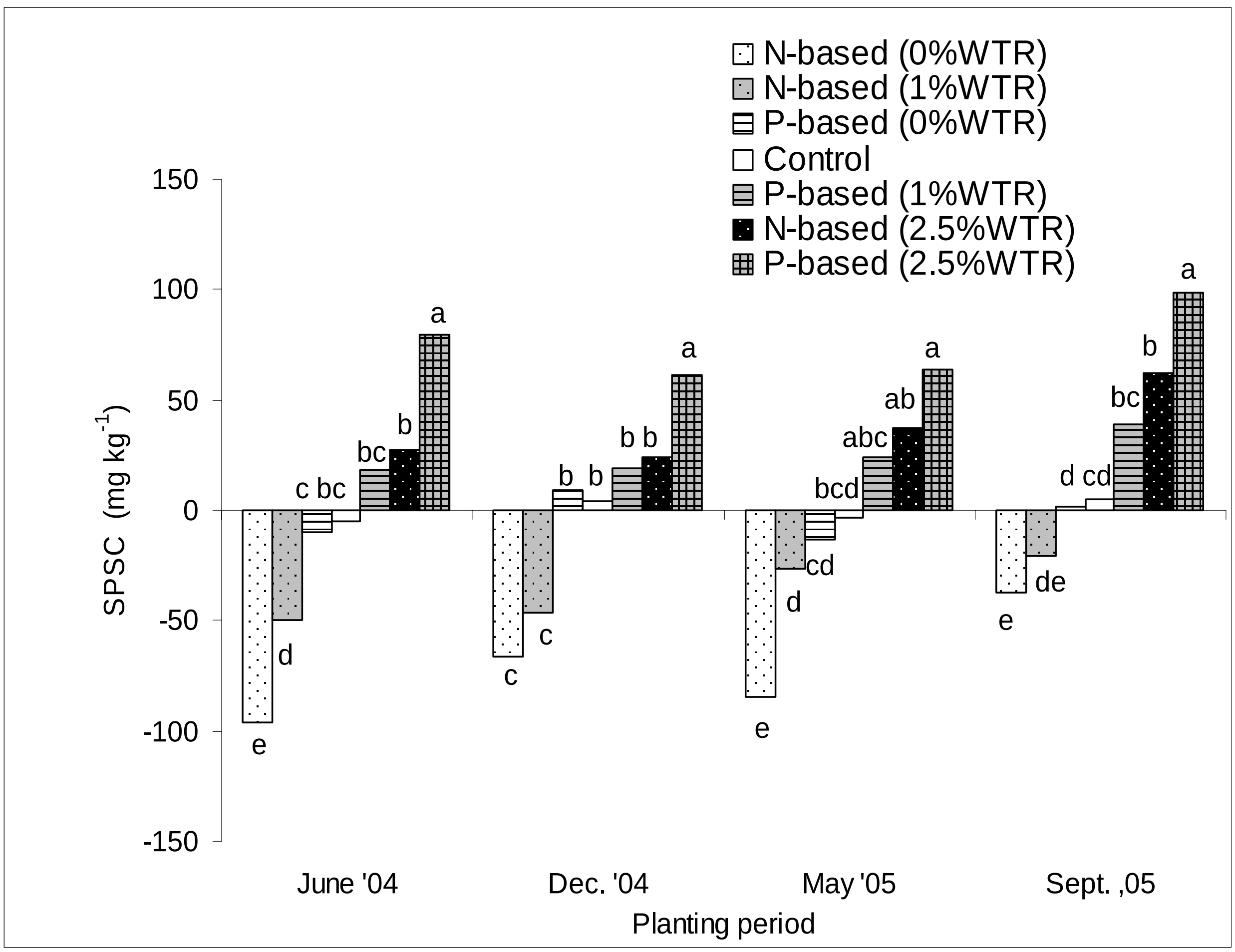


Figure 6-2. Soil phosphorus storage capacity (SPSC, mg kg^{-1}) values at different rates of all P-sources and WTR during the glasshouse study over time. Treatments within the same sampling period with the same letters are not different at $p = 0.05$ by Tukey test.

Soil Phosphorus Storage Capacity (SPSC) in the Field Experiment

The SPSC values of samples taken in June 2003, January 2004 and December 2004 from the soil A horizons during the field study are shown in Fig. 6-3. Soils from subsurface horizons are less affected by the surface applied treatments, and had similar SPSC values for all treatments at the E and Bh horizons. The SPSC values of the E-horizon soil samples are similar, negative, and approximately zero indicating saturation with P and inability to hold added P. The SPSC values of the Bh horizon were positive and also similar (~147 mg kg^{-1}) for all treatments. Positive SPSC values, an indication of soil capacity to hold added P, are expected of an Al-rich Bh horizon. The positive SPSC values of Bh horizons agree with findings by other researchers that noted high P retention capacity of the spodic horizon in spodosols compared with surface A and E horizons (Mansell et al., 1991; Nair et al., 1998; Nair et al., 2004). The similarity of the values for the different treatments and at the different sampling periods shows the spodic horizons are less affected by the surface applied treatments; differences in values likely reflects natural variability.

The impacts of the surface applied treatments were obvious in the SPSC values of samples from A horizons (0-5cm). Soil samples from plots amended with P-sources without WTR have negative SPSC values, and SPSC values for the N-based rates were more negative than for P-based rates (Fig 6-3). Treatments receiving WTR had greater SPSC values than equivalent treatments without WTR. Thus, the field results confirm glasshouse results that SPSC values increased with addition of WTR and decreased with P added to the soil. The SPSC values of the time zero soil samples were affected by chemical properties of the P-sources, as observed in the glasshouse study (Fig. 6-4a).

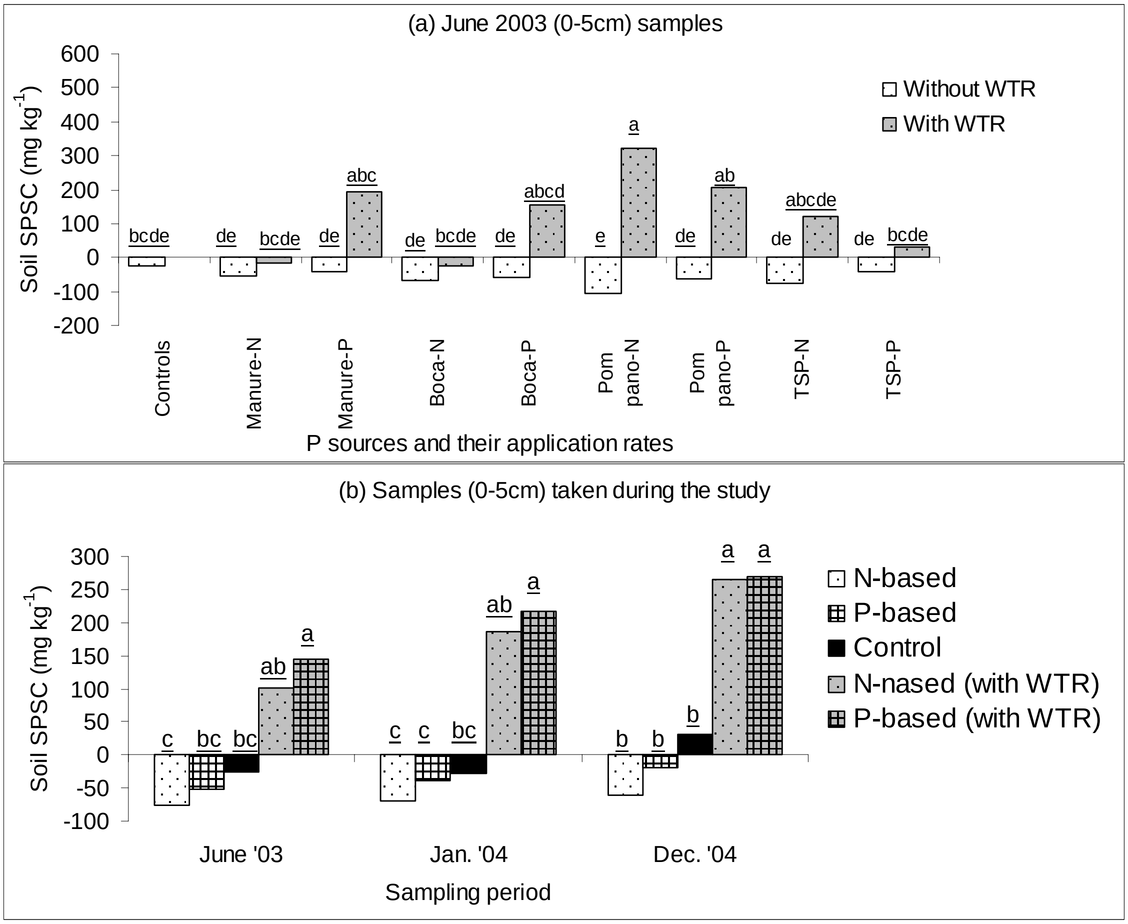


Figure 6-3. Soil phosphorus storage capacity (SPSC, mg kg^{-1}) values of A horizon (0-5cm) samples from the field in (a) June 2003 as affected by the different treatments and (b) June 2003 – Dec. 2004 as affected by P rates and WTR. (Treatments in (a) ending in P, and N, are P-based and N-based rates of the sources, respectively). Treatments in (a) or within the same sampling period in (b) with the same letters are not different at $p = 0.05$ by Tukey test.

Soil Phosphorus Storage Capacity (SPSC) and Plant Growth in the Glasshouse Study

The absolute values of plant yields and P concentrations varied with P-sources, P-source application rates and the amounts of WTR added. For most of the P-sources and at either application rate, plant yields and P concentrations values were greatest in the absence of WTR and least with 2.5% WTR. In most cases, the smallest plant yields and P concentrations were observed at 2.5% WTR applied to P-based rates for each P-source.

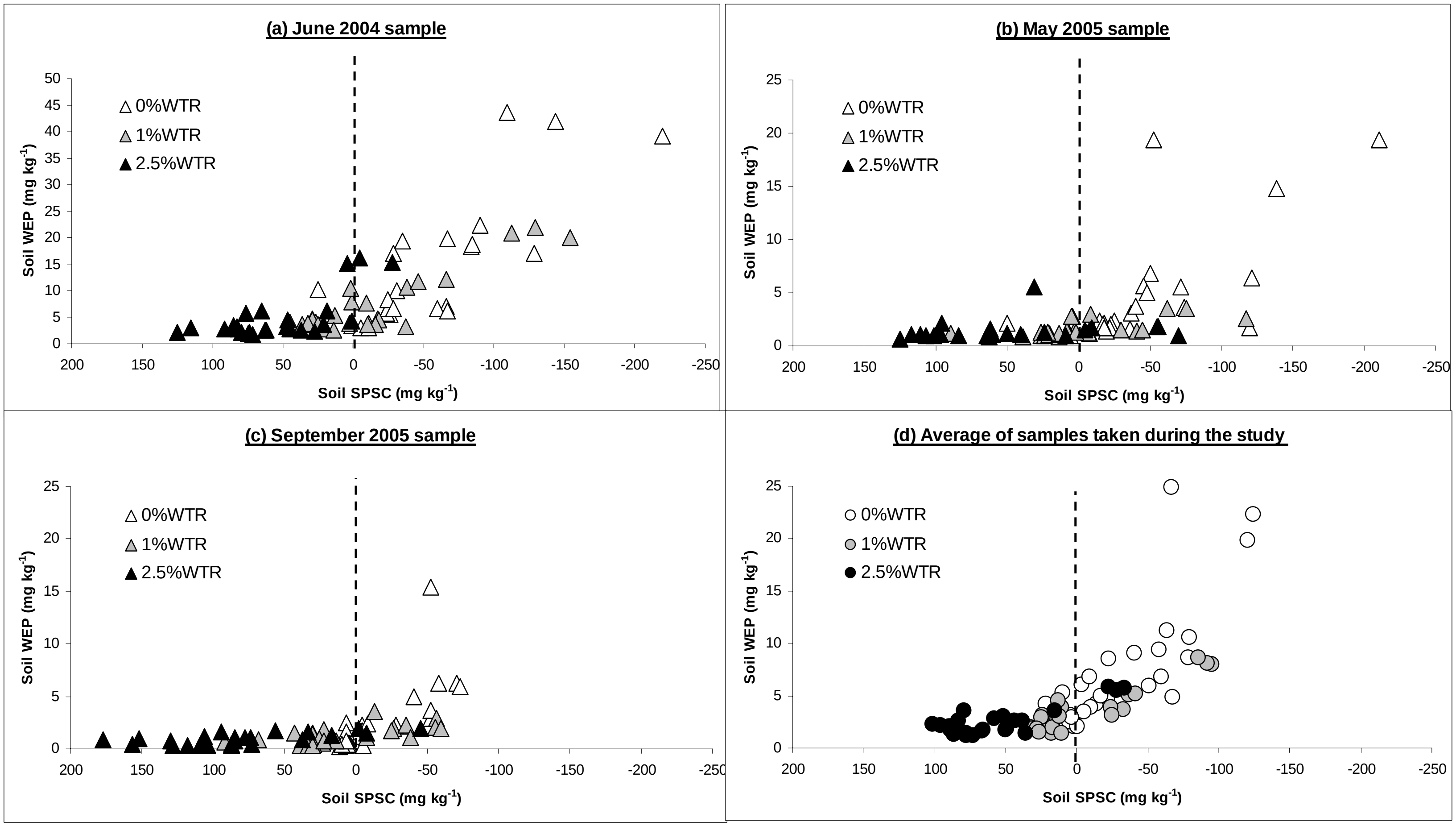


Figure 6-4. Soil P storage capacity (SPSC, mg kg^{-1}) and water extractable P (WEP, mg kg^{-1}) values of soil samples obtained during the glasshouse study in (a) June 2004, (b) May 2005, (c) September 2005, and (d) averaged over all dates. Note the difference in y-axis scales for the June 2004 sampling.

Soil soluble P, indicated by the WEP values, increased with decreasing (more negative) soil SPSC values in the glasshouse study. However, the rate of change in the WEP values was greater below (negative SPSC) than above (positive SPSC) zero-SPSC, suggesting a change point at zero SPSC value (Fig. 6-4). Similar trends were obtained from the field experiment data, which also indicated a change point at zero soil SPSC value (Fig. 6-5). Thus, application rates of the P-sources to the zero soil SPSC value is accompanied by minimal soil soluble P and could be environmentally friendly. However, below zero SPSC value (negative values resulting from either greater soil P or smaller Fe+Al), there could be concerns for greater P loss from the soils due to increasing soil soluble P. The zero SPSC value is equivalent to PSR of 0.15, suggested to be an environmental threshold (Breeuwsma and Silva, 1992; Nair and Harris, 2004).

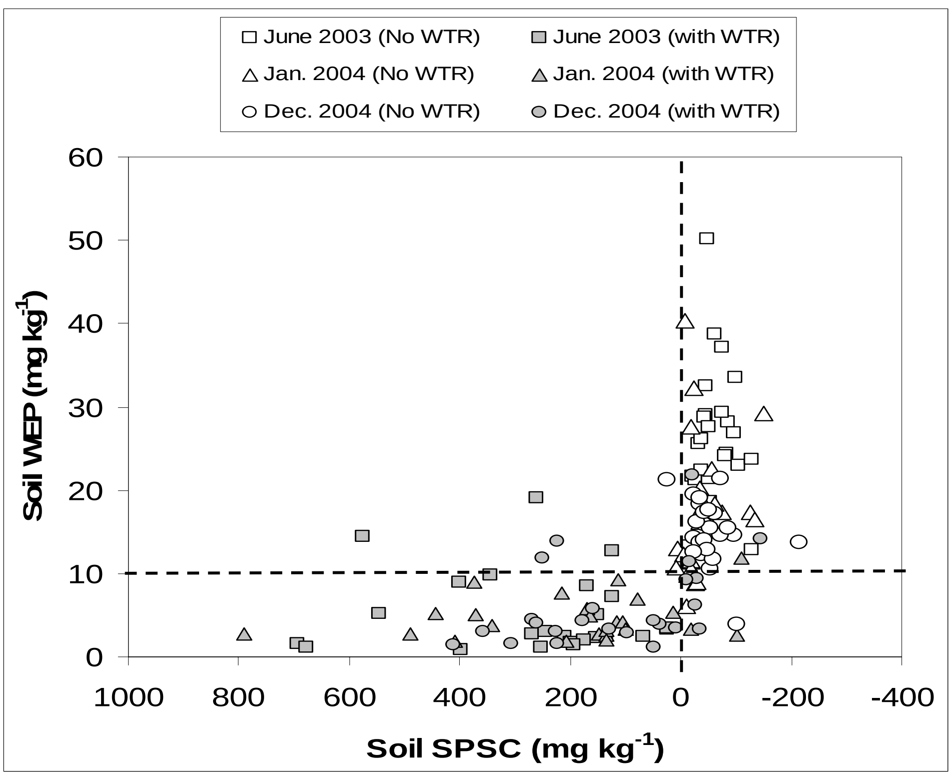


Figure 6-5. The soil phosphorus storage capacity (SPSC, mg kg^{-1}) and water extractable P (WEP, mg kg^{-1}) values of soil samples obtained from the A horizon (0-5cm) during the field study.

Most WTR-amended soils in both the glasshouse and the field studies had greater than zero (positive) soil SPSC values. However, some soils amended with WTR still had negative SPSC values, indicating insufficient added WTR. This is expected because of the variations in the chemical compositions (Al, Fe, and P concentrations) in the P-sources in addition to the rate of P applications. Thus, both the glasshouse and the field studies show that the amount of WTR needed to achieve zero soil SPSC value depends on the compositions and application rates of the applied P-sources.

Zero SPSC values (corresponding to PSR value of 0.15) have been suggested (Breeuwsma and Silva, 1992; Nair and Harris, 2004) as a conservative environmental threshold, and could be recommended as agro-environmental threshold based on the rationale that agronomic threshold is below environmental threshold. Hence, no negative agronomic impact is expected at environmental threshold, which is expected to be greater (3 times) than agronomic threshold. The processes by which crops access soil P are different from those that determine susceptibility to solubilization by subsurface leaching or surface runoff (Kleinman et al., 2000). Plants can solubilize soil water-insoluble P compounds and enhance P uptake by organic acids produced in root exudates. Thus, STP can be maintain at levels that optimize crop yields while minimizing the risk of offsite P transport (Higgs et al., 2000), and WTR application can be based on agronomic threshold.

The range of P concentrations for the first bahiagrass crop (1.5 and 6.4 g kg^{-1}) contains the critical P concentration value of ~2.0 g kg^{-1} identified by Cate-Nelson (1977) type of approximation (Fig. 6-6). The critical (agronomic threshold) P concentration can be defined as the concentration above which there is no plant yield response to increased P concentration. Below a P concentration of 2.0 g kg^{-1}, the first bahiagrass crop dry matter yield was reduced and, little or no response in the plant DM yield to increasing P concentrations was observed above 2.0 g kg^{-1} P concentration. Kincheloe et al. (1987) indicated tissue P concentrations of 2.1 to 4.0 g kg^{-1} are within sufficiency range for grass production. Hence, the 1.6 to 1.7 g kg^{-1} P concentrations observed in pastures (which include bahiagrass) by Adjei et al. (2000) were considered limiting.

Ryegrass P concentrations ranged between 1.8 and 6.3 g kg^{-1}. Ryegrass dry matter yield did not respond to increasing plants P concentration (Fig. 6-6) because the P concentration range observed were greater than the 1 g kg^{-1} critical value suggested for the plant by Hylton et al. (1965). The critical value could not be clearly identified in the second bahiagrass crop (Fig. 6-6). Previous studies have indicated that a reduction in yield-producing capability of organic amendments P (by 20-70%) in the next season following initial fresh P-source application, and continued decline in subsequent seasons (Bolland and Gilkes, 1990). The second bahiagrass was cropped between 12 and 15 months after treatment application and in a pot which had previously and continuously cropped for 11 months. Thus, P deficiency can explain the little response of second bahiagrass crop to increasing plant P concentration. The greater P concentrations during P deficiency periods indicate a "Steenbjerg effect", which is increasing plant nutrient concentrations during nutrient deficiency (Steenbjerg, 1951; Bates, 1971). As earlier explained, the nutrient deficiency destroys potential for growth, but the plants continue to accumulate the nutrient (Ulrich and Hills, 1967; Jones, 1967; Bates, 1971)

The first bahiagrass cropping, which gave plant P concentrations range that includes 2 g kg^{-1} critical value, is free of the Steenbjerg effect and can be used to locate the agronomic critical SPSC value.

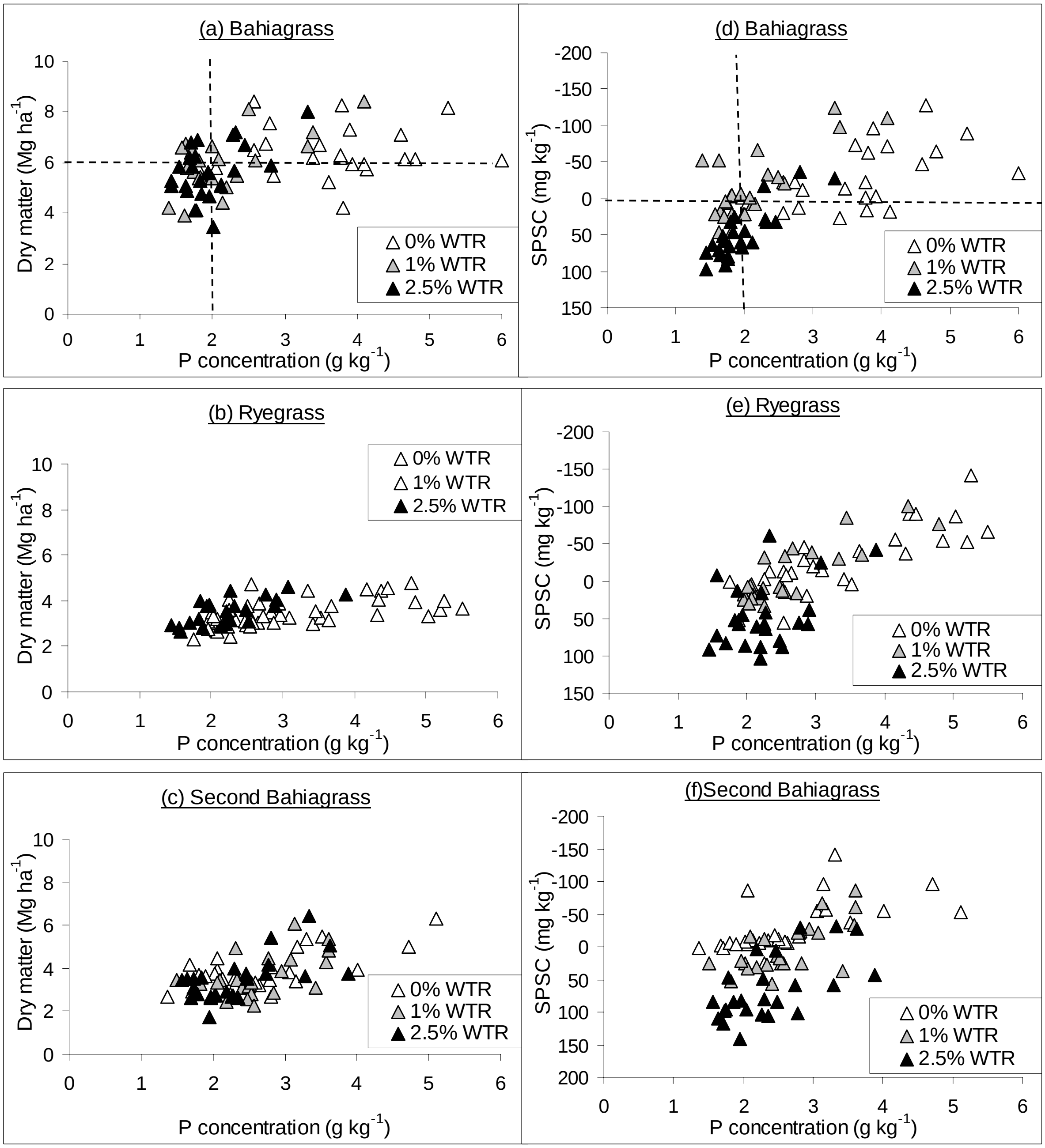


Figure 6-6. Plant dry matter yields and soil P storage capacity (SPSC, mg kg^{-1}) values as a function of plant P concentrations for first bahiagrass crop (a, d), ryegrass (b, e) and second bahiagrass crop (c, f).

Among the six common statistical models available to relate soil test P (STP) to plant yields (Cate-Nelson, linear plateau, quadratic plateau, quadratic, and exponential Mitscherlich type equations), Cate-Nelson method was selected as the best for guiding fertilization recommendations (Mallarino and Blackmer, 1992). The soil SPSC values at planting of the first bahiagrass crop decreased (greater negative values) with increasing tissue P concentrations, and the identified critical P concentrations (2 g kg^{-1} for first bahiagrass) was located at zero soil SPSC value by Cate-Nelson method (Fig. 6-6).

The glasshouse study indicates that by applying either a P-source or WTR (or both) to attain a zero SPSC value will ensure sufficient P concentrations in the plant for growth without negative environmental impacts. Similarly, zero SPSC value also ensured plant P concentrations of 2 g kg^{-1} in the field study (Fig. 6-7). An SPSC value of zero could serve not only as agro-environmental threshold, but also as basis for determining the rates of WTR to be applied. The P-sources can be applied at any rate without negative environmental impact if sufficient WTR is applied to achieve an SPSC value of zero. Applying WTR to attain a zero soil SPSC value will keep the soil soluble P below the change point and above the optimum plant P concentration. Application rates of WTR based on desired soil SPSC values will ensure applying the amount needed for optimum plant growth with no fear of excessive P immobilization.

The SPSC values and amendment P storage capacity (APSC) values (synonymous to SPSC) can be used to determine the amount of WTR needed to be applied to a P impacted soil or co-applied with the P-sources. The SPSC-based rate will not only account for the P, Al, and Fe concentrations in the residuals and the soil, but the threshold soil P is also considered in the calculation. Thus, the WTR rate based on desired SPSC value will ensure a soil P level below the environmental threshold as well as sufficient P level to meet plant needs.

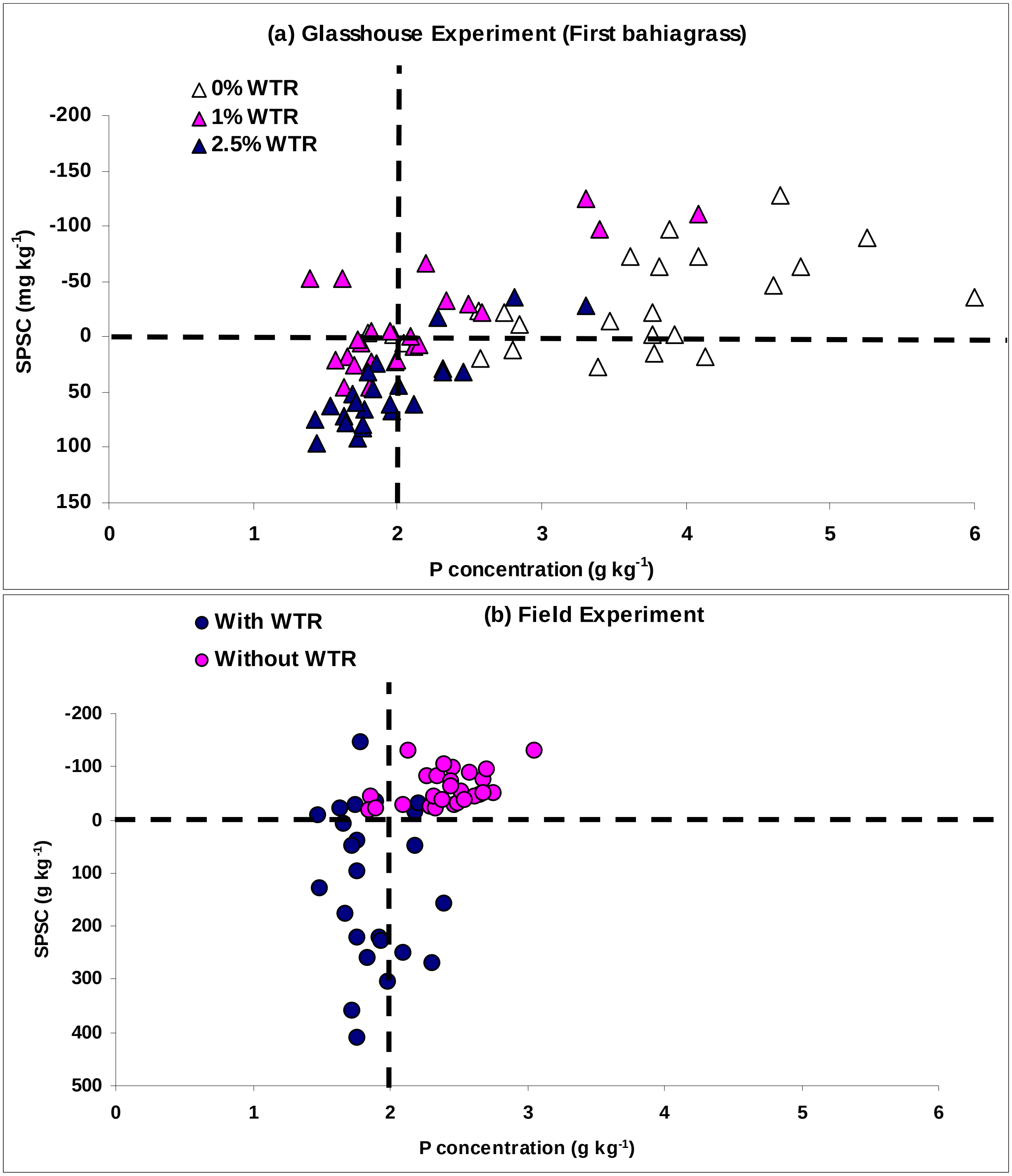


Figure 6-7. Soil P storage capacity (SPSC) values as a function of plant P concentrations in samples taken during (a) glasshouse study (Time zero soil vs. first bahiagrass crop P concentrations) and (b) field experiment (Time zero SPSC of 0-5cm soil samples vs. yield-weighted P concentrations for the 2003 and 2004 harvests.

The amendment P storage capacity (APSC) of the WTR and the P-sources could be estimated by modifying Equation 6-1 to include PSI instead of PSR. Thus, APSC of the P-sources ($APSC_{source}$) and WTR ($APSC_{WTR}$) can be calculated as in Equation 6-4.

$$APSC\ (mg\ P\ kg^{-1}) = [(0.15-PSI)*(Al_{ox} + Fe_{ox})]*31 \qquad \textit{Equation 6-4}$$

Where PSI = Phosphorus sorption index = $[(P_{ox})/(Al_{ox} + Fe_{ox})]$

The amount of WTR to be added could then be determined from Equation 6-5 as:

$$SPSC_{soil} * Weight_{soil} + APSC_{source} * Weight_{source} + APSC_{WTR} * Weight_{WTR} = 0 \qquad \textit{Equation 6-5}$$

The SPSC value of the soil and APSC value of P-source and the WTR could be estimated from their chemical compositions. The weight of the P-sources is known from the application rate and the weight of soil could be determined from the land area to depth of impact (depending on AM; 15 cm depth if incorporated, or 5 cm when surface applied) and the soil bulk density. Thus, the only unknown in Equation 6-5 is the weight of WTR, which can be determined by substituting the known values into the equation.

Equation 6-5 can be used to calculate amount of WTR needed to achieve a particular soil SPSC value under any given condition. For example, to decide on the amount of WTR needed to increase a highly P-impacted soil SPSC value to 5, the equation is used without P-sources parameters (since no P-source is added) and the formula equated to five (5) instead of zero.

Based on the SPSC and APSC values, the amount of WTR needed to be applied to a P impacted soil or co-applied with the P-sources can be determined. The SPSC value observed in time zero soil samples of each treatment at the three rate of WTR are shown on Table 6-2. Also included are the amounts of WTR needed to achieve 0 mg SPSC kg^{-1} at the two rates of the four P-sources. At the P-based rate, applying at least 1% WTR gave SPSC values greater than zero in all the P-sources, which indicated more WTR was applied than necessary. However, at N-based rates more than 1%, but less than 2.5% WTR, is needed by manure, Pompano and TSP treatments; and greater than 2.5% WTR is needed by Boca Raton biosolids to achieve 0 mg SPSC kg^{-1}.

Table 6-2. Observed SPSC values (mg kg^{-1}) of time zero soils at 0, 1, and 2.5% WTR and calculated amounts of WTR needed to achieve 0 mg SPSC kg^{-1} when co-applied with the four P-sources at the two P-source rates (glasshouse study).

P-source rate	P-source	WTR Rate			WTR (g) needed to achieve 0 mg SPSC kg^{-1}
		0% †	1% ‡	2.5%¶	
P-based	Manure	-25	29	87	25
	Boca Raton biosolids	-26	5.5	75	90
	Pompano biosolids	-21	0.3	60	58
	TSP	-12	39	96	15
N-based	Manure	-78	-50	53	140
	Boca Raton biosolids	-158	-132	-9.4	726
	Pompano biosolids	-64	-15	43	294
	TSP	-84	-2.3	23	27

†0 g of WTR applied per pot
‡115g of WTR applied per pot
¶287 g of WTR applied per pot

Summary and Conclusions

Applying P-sources at P- based rates results in soil SPSC values close to 0 mg kg^{-1}. However, when the P-sources were applied at N-based rates, the SPSC values were negative and the magnitude depended on P_{ox}, Al_{ox} and Fe_{ox} of the P-sources. Similarly, co-application of equal amounts of the same WTR with different P-sources will result in different soil SPSC values, reflecting different chemical compositions (Al_{ox} and Fe_{ox}) of the P-sources.

Application of different WTRs at the same dry weight basis could result in negative agronomic and or environmental impact depending on WTR and P-sources Al, P and Fe composition. A WTR with greater oxalate Al and Fe concentrations will result in greater SPSC values and, hence, lower soil soluble P concentration more than a WTR with lower Al concentrations. Application rates of WTR based on desired soil SPSC value will ensure applying the amount needed for optimum plant growth with no problem of excessive plant available P immobilization. The zero soil SPSC value was identified as the critical point above which the plant P concentrations can be sufficiently reduced to reduce plant yields and below which the soil soluble P and, hence, potential P loss may increase. Amendment P storage capacity (APSC), an equivalent term of SPSC for the P-sources, needed for the calculation of WTR rate was also suggested.

This study shows application rates of the P-sources and WTR to "ZERO" SPSC values will optimize both agronomic and environmental benefits of the residuals.

CHAPTER 7
EFFECTS OF A WATER TREATMENT RESIDUAL (WTR) ON RUNOFF AND LEACHATE PHOSPHORUS LOSSES

Introduction

Phosphorus losses from agricultural land have been implicated as one of the main causes of reduced water quality in the USA (USEPA, 2000; Boesch et al., 2001). An adequate understanding of pathways for P loss from agricultural fields would enhance management techniques to minimize the loss. Studies of P loss have focused primarily on movement of P via the soil surface (runoff) with less attention to subsurface (leachate) loss pathways. The focus on runoff was based on the assumption that most soils contain sufficient P sorbing oxides to maintain subsurface soil solution P concentrations below euthrophication thresholds (0.01 to 0.05 mg L^{-1}, Sims et al., 1998). However, subsurface leaching of P could be equally as important as runoff P inputs into surface waters in areas with shallow ground waters and sandy soils with little P sorbing capacity (Eghball et al., 1996; Sims et al., 1998; Novak et al., 2000; Elliott et al., 2002a). Such areas and soils are common in Florida and other coastal plain regions of the US.

Approximately 3.4 million hectares in Florida have been mapped as Spodosols with sandy texture and poor P sorption capacities in A and E horizons (Collins, 2003). In Florida, the spodosols are characterized by high water tables located between the Bh and the A horizons during the summer rainy season, which recede to 125 cm during drier months (Soil Survey Staff, 1996). Lateral water movement of rainfall that infiltrates the soil during the high water table season can transport P to surface drainage ditches (Burgoa et al., 1990; Mansell et al., 1991). Thus, P loss evaluations in such soils must account for both runoff and leaching.

The phosphorus loss through runoff and leaching can also vary with applied P-source, as the solubility, bioavailability and transport potential of P varies among biosolids, manures, and fertilizer types (Sharpley and Moyer, 2000; Brandt et al., 2003; Leytem et al., 2004; Elliott et al., 2005). Aside from availability of P in the P-source, the amount of P applied could also influence the amount of P loss. An example is nitrogen (N)-based nutrient management of the organic source of P, which could enhance P loss. As the rate considers only nitrogen, P is often over applied. The large soil P loads that accompany N-based amendment rates can cause soil P accumulation to levels above those needed for optimum crop production (Reddy et al., 1980; Pierzynski, 1994; Maguire et al., 2000).

The forms of phosphorus that promote organism growth, referred to as bioavailable P (BAP), include dissolved P and bioavailable particulate P (Sharpley, 1993a,b; Myers and Pierzynski, 2000). Dissolved reactive P results from desorption, dissolution, and extraction of P from soil amendments including biosolids, manure, or recently applied P fertilizer (Daniel et al., 1998; Sauer et al., 1999; Sharpley et al., 1999). Bioavailable particulate P includes a portion of P bound to soil particles or to organic matter that enters surface water bodies and is subsequently made available for aquatic organisms. Studies on environmental P losses based on water soluble P, without accounting for bioavailable particulate P, may be inadequate as both dissolved forms and portions of colloidal P forms could promote eutrophication. Iron strip extractable P (ISP) has been shown as a good measure of BAP (Sharpley, 1993a, b; Myers and Pierzynski, 2000). In an incubation study with runoff as the sole source of P, the growth of P-starved *selenastum capricornutum* was strongly related ($r^2 = 0.96$) to the runoff ISP (Sharpley, 1993a). The amount of P extracted from runoff by the Fe-oxide strips adequately estimated the BAP content of the runoff that was potentially available for uptake by freshwater organisms.

Reduction of soil soluble P following application of water treatment residual (WTR) has been reported (Peters and Basta, 1996; Basta and Storm, 1997; O'Connor and Elliott, 2001;

O'Connor et al., 2002a; Elliott et al., 2002b; Elliott et al., 2005; Novak and Watts, 2005). Surface application of WTR has been shown to reduce runoff P (Peters and Basta, 1996; Basta and Storm, 1997; Dayton et al., 2003). Also, leachate P was reduced when WTR was incorporated into the soil (Elliott et al., 2002b; O'Connor et al., 2002a; Novak and Watts, 2004; Dayton and Basta, 2005). Surface co-application of P-sources and WTR could be a practical way of applying these residuals to an established pasture. However, the impact of the surface applied sources of P and the WTR on P loss through both runoff and leaching needs to be quantified. The objective was to determine the effects of surface applied P-sources and an Al-WTR on runoff and leaching P losses in a rainfall simulation study.

Materials and Methods

Rainfall Simulation Experiment

The same P-sources used in the glasshouse and field study (poultry manure, Boca Raton biosolids, Pompano biosolids, and TSP) were surface applied at rates equivalent to 56 kg P ha^{-1} and 224 kg P ha^{-1} to represent the low and high soil P loads typical of P-based and N-based amendments application rates, respectively. The soils also received Al-WTR surface applied at 0 or 1% (22.4 Mg ha^{-1} oven dry basis) on top of the applied P-sources. Soils without any added P-source, but with and without WTR, were included as controls.

The rainfall simulation was carried out as prescribed in the National Phosphorus Research Project indoor runoff box protocol (National Phosphorus Research Project, 2001). The protocol specifies the dimension of runoff boxes (100 cm long, 20 cm wide and 7.5 cm deep). However, the box design was modified to quantify leaching of P in addition to runoff P by adding a second box (no soil and water tight) under the first in a double-decker design (Fig. 7-1). This design allowed collection of runoff and leachate simultaneously.

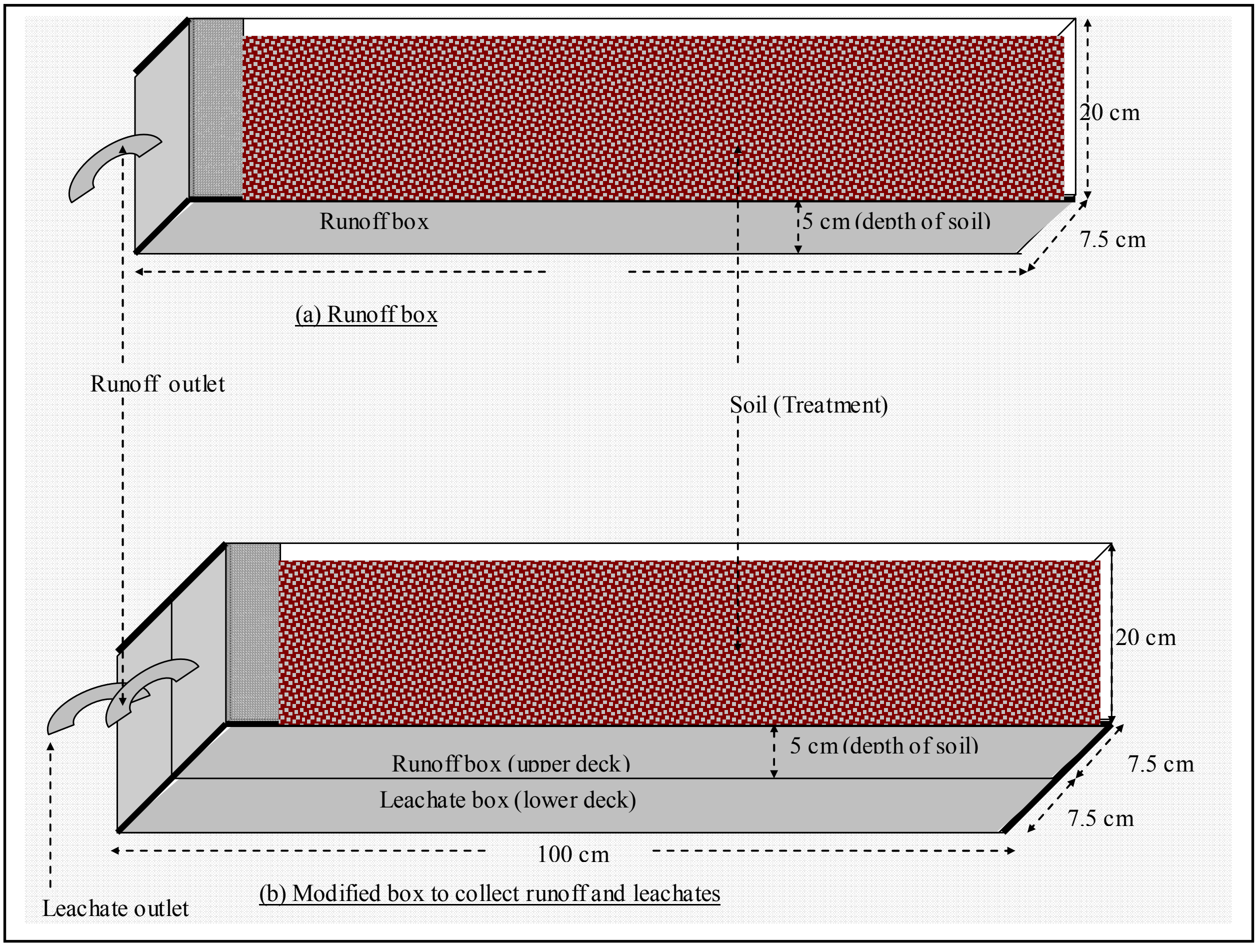


Figure 7-1. National P Research project (a) runoff box design and (b) box design modified to collect runoff and leachate simultaneously.

The top boxes were packed with 5 cm depth of soil to a bulk density of 1.4 g cm^{-3}. Treatments were surface applied as uniformly as possible (P-source first, and then WTR) a day after wetting the soil to near saturation. The treated soils were all leveled with the lower edge of the boxes. Three boxes each (3 replicates) of the eighteen (18) treatments were prepared, and rainfall events conducted 3, 5 and, 7 days (representing 1^{st}, 2^{nd} and 3^{rd} rainfall events, respectively) after the initial wetting on each of the treatments. The rainfall intensity, 7.1 cm h^{-1}

(equivalent to a 10-y, 24-h rain), was applied from a height of 3 m above the soil in boxes slanted at 3% slope. The flow rate was measured before each simulation rain event to ensure a flow rate of 210 mL sec^{-1} stated in the protocol. Also the uniformity of the rain intensity in simulation area was ensured and calibrated before each rain event. Thirty (30) minutes of runoff generated during each rainfall event were collected from each soil box at the down-slope end of each box and the volumes recorded. In addition, leachate was collected continuously during each rainfall event. Representative, well mixed samples (250 mL) of runoff and leachate were collected for analysis. Another sub-sample of the runoff was filtered (0.45um) before P analysis for dissolved P determination.

Leachate and Runoff Analyses

Soluble reactive P (SRP) concentrations were determined on the filtered runoff (R-SRP) and the leachate (L-SRP) samples colorimetrically with the Murphy and Riley method (1962). The Iron-strip P concentrations (a measure of BAP) in the runoff and the leachates were determined by shaking 50 mL samples (diluted with 30 mL of deionized water) with Fe-impregnated (0.65 M $FeCl_3$ in 0.6 M HCl) filter paper. The P adsorbed was then extracted with 50mL of 0.1 M H_2SO_4 and analyzed colorimetrically (van der Zee, 1987).

Total phosphorus concentrations were measured on the filtered runoff (total dissolved P, TDP) and the leachate (LTP) samples after digesting 10 mL of the samples with 0.5 mL 6N H_2SO_4 and 0.15g of potassium persulfate in an autoclave for 1 h (Pote and Daniel 2000a and b). Total P in unfiltered runoff samples (TRP) was determined by digesting 5 mL of the samples with 1mL of 6N H_2SO_4 and 0.3g of potassium persulfate on a digestion block and then diluted by adding 10 mL of water. All digested samples were analyzed for P colorimetrically (Murphy and Riley, 1962). Particulate phosphorus (PP) concentration was calculated by subtracting TDP from the total P (TP) of each sample. Dissolved organic P (DOP) was assumed to be the difference between SRP and TDP. Leachate and runoff pH and EC were also determined on each sample.

Flow-weighted P concentrations were calculated for the runoff and the leachate by summing the products of the P concentrations and volumes for the three rain events and dividing by the total volume of the events. The runoff and leachate P losses (mg) were calculated as the product of flow-weighted concentrations (mg L^{-1}) and the total runoff and leachate volumes (L). Masses of TP and BAP loss (mg) were determined by summing the masses of runoff and the leachate P loss of each form.

Statistical Analysis

Normal probability plots and residuals of the data were studied to ensure the samples satisfied the assumptions of normality, constant variance and independence. The assumptions of normality and constant variance were violated by the leachates and runoff TP, BAP, and SRP concentrations and P losses, and log transformation was shown to be appropriate by Box Cox to correct the violations (SAS Institute, 1999). The data were log-transformed to normalize the data and stabilize the variance. Analysis of Variance (ANOVA) was performed on the various forms of runoff and leachate P loss (concentrations and masses) data (or the transformed data as applicable) using PROC GLM to determine significance treatment effects (SAS Institute, 1999). The data were analyzed as a RCBD using the model: $Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \beta\gamma_{jk} + \alpha\beta\gamma_{ijk} + \varepsilon_{ijkl}$; where α_i is effect of i^{th} P-source (i = manure, Boca Raton biosolids, Pompano biosolids, and TSP); β_j effect of j^{th} source rate (j = P-, and N-based rates); γ_k effect of k^{th} WTR rate (k = 0, and 1%) and other terms are the 2-way ($\alpha\beta_{ij,}$ $\alpha\gamma_{ik,}$ and $\beta\gamma_{jk}$), and 3-way ($\alpha\beta\gamma_{ijk}$) interactions, and error (ε_{ijkl}) terms. To compare the treatments means including the control, the 18 treatments were analyzed using one factor (treatment) model: $Y_{ij} = \mu + \alpha_i + \varepsilon_{ij}$; where α_i is effect of i^{th} treatment and ε_{ij} is the error terms. When significance was indicated by ANOVA, means multiple comparisons by Tukey test were performed at 0.05 significance level using SAS.

Results and Discussion

Runoff and Leachate pH and EC

The pH values of the leachates ranged from 5.55 for TSP (at low rate with WTR) to 7.10 for manure (with or without WTR). Runoff pH values followed similar trends, with the lowest value (6.32) associated with the low rate of TSP, and the greatest pH value (7.32) observed in manure applied at the high rate with WTR.

The TSP had minimal impact on pH values in runoff and leachate, with pH values similar to the values for control treatments. The pH values were also similar for treatments with and without WTR for each P-source. The minimal impacts of TSP and WTR on runoff and leachates pH were expected because the P-source pH values were similar to the range of pH values (pH = 5.5 – 5.9) of soil used for the study (Table 2-1). Greater runoff and leachate pH values were observed in manure treatments (at the high application rate), owing to the large Ca concentration and alkalinity of the material.

The EC values of leachate and runoff followed similar trends as the pH (i.e., greatest in manure, high rate treatments, and least in TSP, low rate treatments) and could similarly be explained. Novak and Watts (2005) also reported minimal impacts of WTR on soil pH and EC values at rates as great as 6 % WTR. Greatest EC and pH values were observed in manure amended soils during the glasshouse study, likely as a result of poultry feed additives, which can increase the EC of manure.

Runoff and Leachate P Forms and Concentrations

The P concentrations in runoff and leachate (flow-weighted over the three rainfall events) are summarized in Figs. 7-2 and 7-3, respectively.

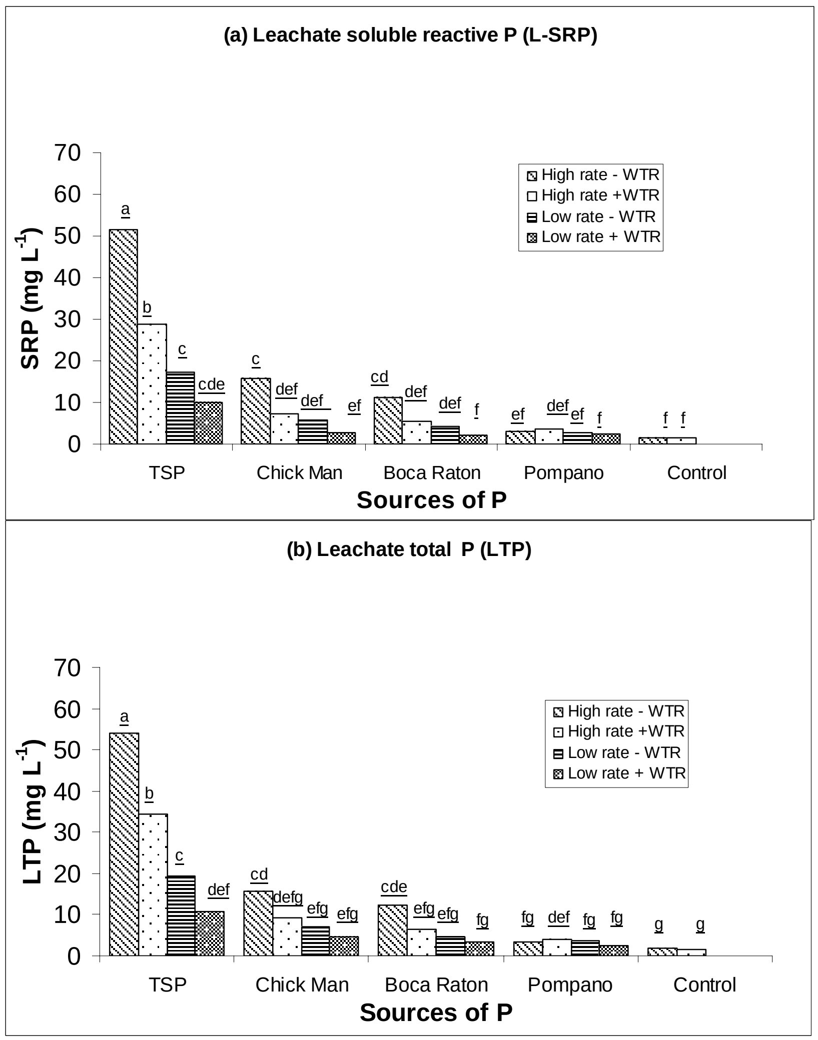


Figure 7-2. Leachate flow-weighted mean (a) soluble reactive P and (b) Total P concentrations for the various treatments. (Treatments bars capped by the same letters are not different at $p = 0.05$ by Tukey)

Soluble P dominated total P concentrations in leachate (Fig. 7-2 a) in all treatments (~85% in TSP, and > 60% in the organic sources). In the absence of WTR, the leachate flow-weighted TP concentrations were greater in TSP treatments than in the organic source treatments, similar in manure and Boca Raton biosolids treatments, and greater in Boca Raton biosolids than in Pompano biosolids treatments (Fig. 7-2 b). Similar trends were noted for the leachate flow-weighted soluble reactive P concentrations (Fig. 7-2a), and reflected the P-source solubility.

The flow-weighted TP and SRP concentrations in leachates were reduced by surface applied WTR for both application rates of TSP, but the reductions of the TP concentrations in organic sources of P treatments by WTR were not significant (at $p = 0.05$). Greater TP and SRP concentrations in leachates were observed in the manure and Boca Raton biosolids treatments applied at N-based rates in the absence of WTR, but the concentrations were not greater than those for the P-based rate of TSP. Thus, the P concentrations at high rate of organic sources of P were not greater than observed at the P-based rate of TSP. Applying the moderate water soluble organic source of P (Pompano biosolids) resulted in similar P concentrations in leachates, irrespective of the application rate. The leachate TP and SRP concentrations were small at low rates of organic sources of P and similar to concentrations observed in control treatments. In addition, the leachate TP, and SRP concentrations, at N-based rates of the organic sources of P (in the presence of WTR), were similar to control treatments. Thus, hazards of greater soil P concentrations could be managed by either applying the P-sources at P-based rates, or at N-based rates in combination with WTR. Moderate water soluble P-sources could also be applied at N-based rates, without inducing greater soil P concentrations that can negatively impact the environment.

Runoff soluble reactive-P concentrations (R-SRP) were similar to runoff total dissolved-P concentrations (R-TDP) for most of the treatments (Fig. 7-3). The R-TDP was mostly inorganic; dissolved organic P (DOP) concentrations accounted for less than 5% of the runoff total P (TRP) concentrations in any treatment. Other studies also indicated inorganic P as dominant soluble fraction in the runoff and leachates (Heckrath et al., 1995; Turner and Haygarth, 2000). Total P concentrations (Fig. 7-3) of the runoff (TRP) were greater than the runoff soluble P (R-SRP and R-TDP) concentrations due to the significant contribution of particulate P (PP) to the P loss from the surface applied P-sources. Particulate P concentrations in runoff accounted for >80% of TRP concentrations for the organic sources and about 60% for TSP treatments. The proportion of TRP concentrations as particulate P of the organic sources follows the trend Pompano biosolids (~90%) > Boca Raton biosolids (~85%) > Manure (~80%).

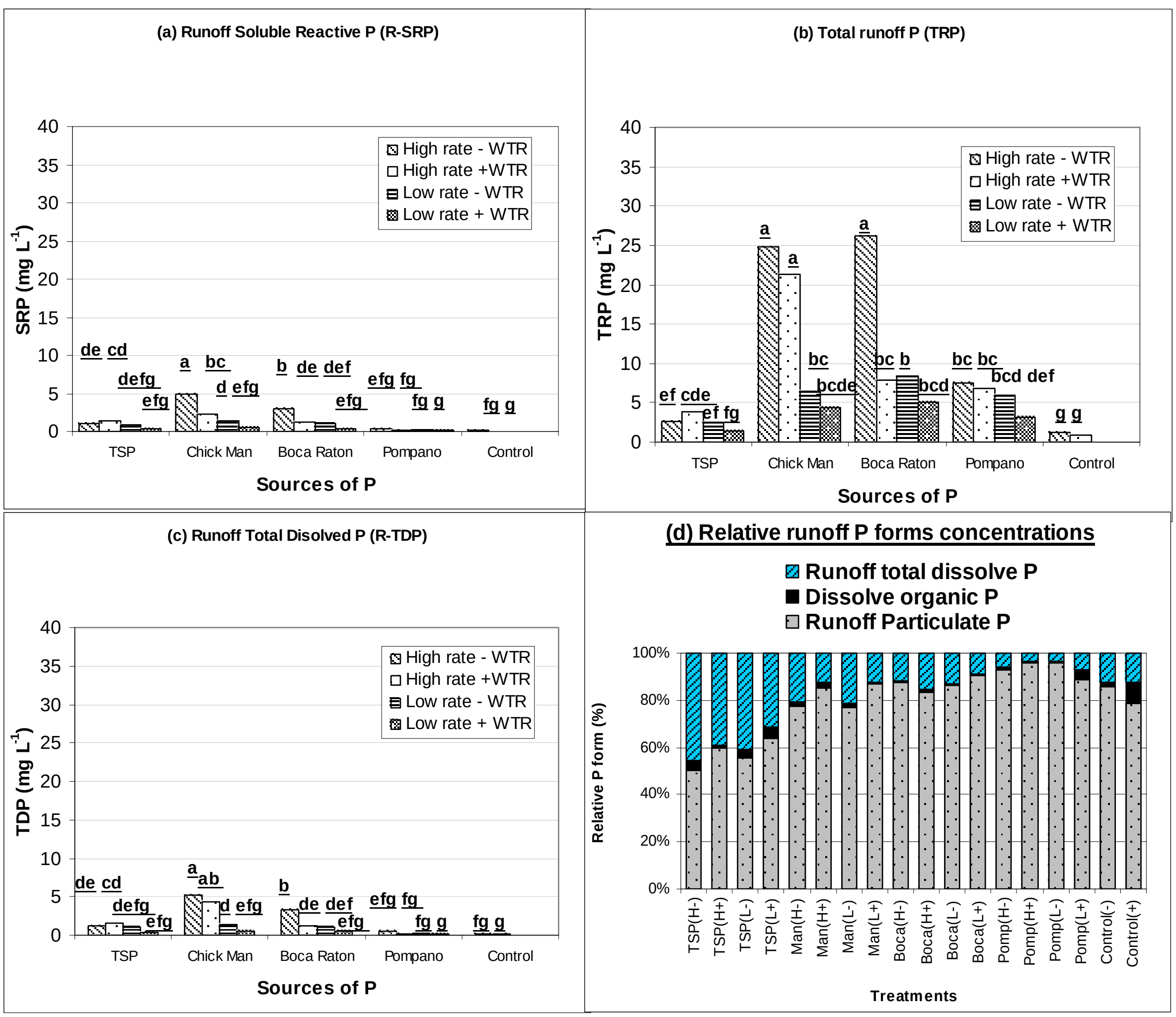


Figure 7-3. Runoff flow-weighted mean (a) soluble reactive P (b) Total P (c) Total dissolved P concentrations and (d) relative P forms concentrations for the various treatments (Treatments followed by the same letters are not different at $p = 0.05$ by Tukey)

The runoff soluble P concentrations (R-SRP and R-TDP) and their percentages of TRP concentrations in the absence of WTR tracked well with the PWEP values of the different organic source of P. The order (PWEP values in parentheses) was manure (18%) > Boca Raton biosolids (11%) > Pompano biosolids (4%). Runoff soluble P for the TSP treatments was much less than in the organic sources despite the large TSP PWEP value (84%) because most of the P lost appeared in leachate.

Runoff and Leachate Bioavailable P Concentrations

The greater particulate P observed in the runoff may confound the estimation of bioavailable P in the aquatic system. Sedimentation losses of the particulate P will reduce effective bioavailability of the particulate P in the lakes compared to TP measured in the lab (Young and DePinto, 1982; Effler et al., 2002). Thus to account for the portion of the particulate P that is bioavailable along with the soluble P, bioavailability of runoff and leachate P (BAP) were estimated using iron strip P method.

The flow-weighted BAP concentrations (Fig. 7-4) followed similar trends for the different treatments as the trends of flow- weighted SRP and TP concentrations in the runoff and the leachate. The BAP concentrations were greater in leachate than runoff, especially for fertilizer P. This is consistent with greater leachate P loss indicated to be significant in Florida soils (Izuno et al., 1991). The BAP concentrations were reduced by adding WTR at both application rates of manure and Boca Raton biosolids (in runoff) and TSP (in leachate). Similar to the leachate TP and SRP concentrations in the absence of WTR, the leachate BAP concentrations values at the N-based rates of organic source of P were smaller than at the P-based rate of TSP.

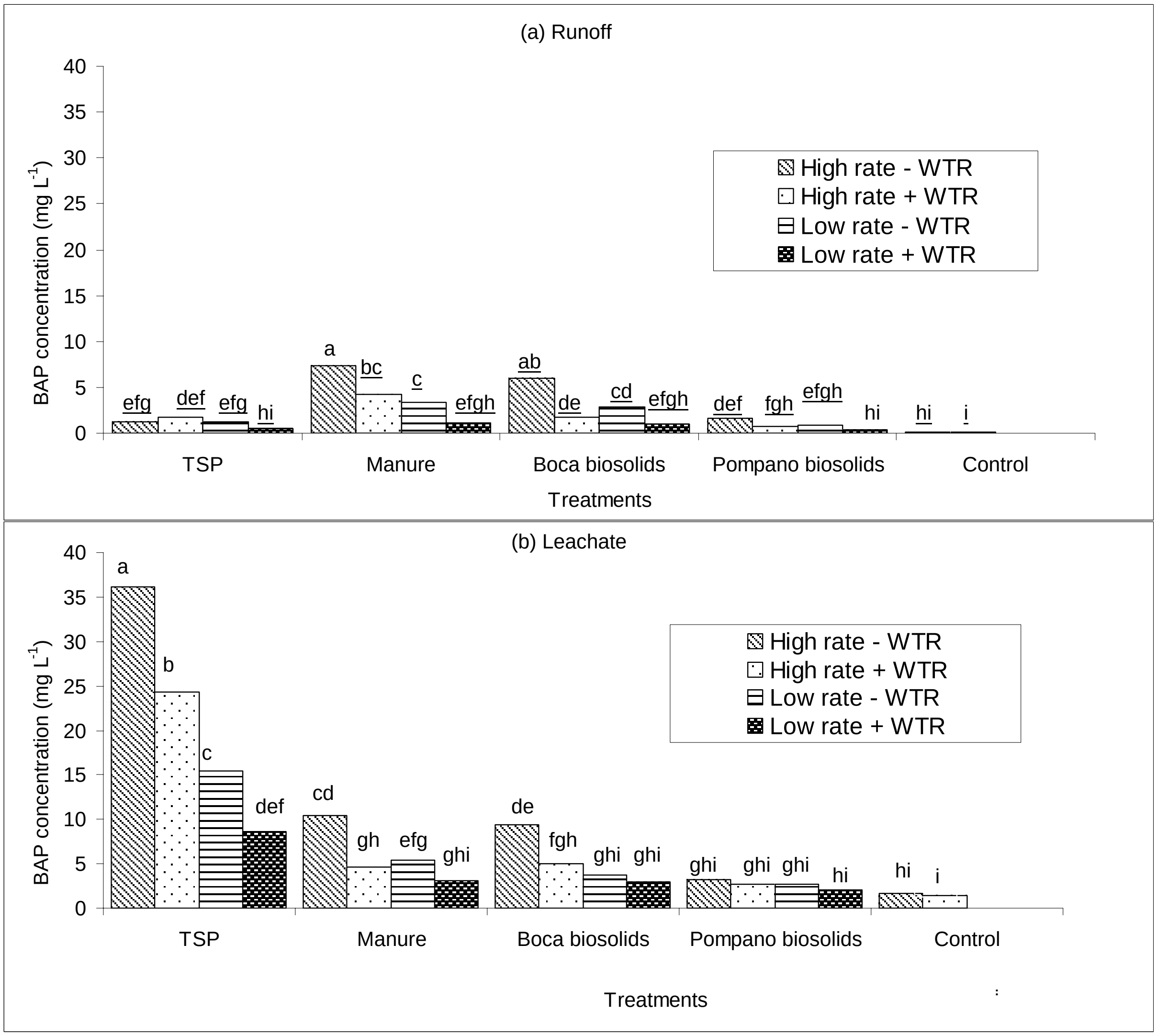


Figure 7-4. Flow-weighted (a) runoff and (b) leachate bioavailable P (BAP) concentrations for the various treatments (Treatments bars capped by the same letters are not different at $p = 0.05$ by Tukey).

Both leachate and runoff BAP concentrations were affected by the source of P. The runoff BAP concentrations at P-based rates were similar in the manure and Boca Raton biosolids treatments, but greater than BAP concentrations in Pompano biosolids treatments. At the N-based rate, the BAP concentration trends were: manure > Boca Raton biosolids > Pompano biosolids, which agrees with the solubility of the organic sources. Leachate BAP concentrations were greater in TSP treatments than in the organic source treatments due to the greater solubility of TSP. The trends of the leachate BAP concentrations at both application rates of the organic sources were similar to the trends observed in runoff at P-based rates. The BAP concentrations were greater in manure and Boca Raton biosolids treatments than in the Pompano treatments. Thus, the BAP concentrations in leachate tracked well with P-source WEP values: TSP (WEP = 175 g kg^{-1}) > Manure (WEP = 4.6 g kg^{-1}) ≈ Boca Raton biosolids (WEP = 5.5 g kg^{-1}) > Pompano biosolids (WEP = 1.2 g kg^{-1}).

Forms of Runoff and Leachate Phosphorus Losses

To account for runoff and leachate volumes, mass of total P losses (runoff and leachate) were evaluated as the products of concentrations (in runoff and in leachate) and their volumes. There were greater P losses (SRP, TDP, BAP, PP and total P) in the first rain event than in subsequent events in both runoff and leachate. Other studies also documented decreasing TP and dissolved P in runoff with successive rainfall events following surface applications of P-sources (Sharpley, 1997; Penn and Sims, 2002; Sims et. al., 2003; Elliott et. al., 2005). The first rainfall event accounted for ~70% of the cumulative soluble and TP losses (runoff plus leachate) from TSP treated soil collected over the three rain events. About 40% of the cumulative P losses (depending on the P-source) also occurred in the first rainfall event from the organic source treated soils.

Similar to the trends of weighted P concentrations, fertilizer P loss was primarily in the leachate, but substantial amounts of soluble P also appeared in leachates from the organic source of P treatments. The masses of leachate P loss were greater in TSP treatments (147 – 746 mg) than in organic source treatments (20 – 126 mg), whereas the runoff TP losses were greater in organic source treatments (41 – 492 mg) than in TSP treatments (16 – 42 mg). The greater runoff P losses from organic sources were due to large amounts of particulate P, which dominated P losses in runoff. Particulate P loss in TSP treated soils was much less (Table 7-1). In runoff, P losses (especially BAP and other soluble reactive P forms) at the N-based application rate of manure and Boca Raton biosolids were smaller when WTR was co-applied. Both TP and SRP losses in leachates from TSP treatments at the N-based rates were reduced in the presence of WTR. However, the particulate P and dissolved organic P (DOP) masses were similar for treatments with and without WTR for all the P-sources.

The masses of P lost as BAP in the leachates and runoff followed similar trends as the soluble and total P losses. The masses of BAP loss in TSP treatments were greater in leachate (133 – 536 mg) than runoff (5 – 23 mg). The total masses of BAP loss were also greater in the absence of WTR (30 – 548 mg) than in the presence of WTR (17 – 464 mg).

The N-based manure treatment, without WTR, resulted in the greatest masses of runoff P losses as TP, SRP TDP, PP and BAP. The runoff TP, PP and BAP mass losses from Boca Raton biosolids treatment at the N-based rate were similar to loses from manure applied at the same rate. However, the runoff P losses as TP, SRP, TDP, DOP and PP from Pompano biosolids (applied at the N-based rate) were less than from the Boca Raton biosolids and manure treatments and similar to the P losses from control treatment (Table 7-1). Thus, the expected greater P hazard associated with N-based rates may not be true for all organic sources of P. Applying a moderate water soluble P-source like Pompano biosolids may pose minimal environmental threat (with respect to P in the runoff), even at a N-based rate.

The absolute values of the BAP losses were generally greater than the SRP losses in most cases, especially in the runoff where a significant portion of particulate P was bioavailable. The proportion of total P mass losses that is bioavailable was greater in TSP than in organic source of P treated soils, and greater in the absence than in the presence of WTR (Fig. 7-5).

Table 7-1. Masses of P forms lost in runoff and leachates.

P-source	Rate (kg ha^{-1})	Mass of P applied (mg)	WTR (%)	Soil P load mass‡‡ (mg)	<--------------------Runoff P (mg)---------------------->						<-------Leachate P (mg)----->				Total P loss	§§Total BAP loss	Percentage of applied P lost as BAP (%)
					TP†	SRP‡	TDP§	DOP¶	PP#	BAP††	TP†	SRP‡	PP#	BAP††			
TSP	224	1680	0	2048	27.3[cd]	11.8[cdefg]	13.0[cdef]	1.20[b]	14.4[c]	11.9[efg]	746[a]	706[a]	40.2[ab]	536[a]	774[a]	548[a]	32.6[ab]
TSP	56	420	0	788	41.7[cd]	15.9[cde]	17.6[cde]	1.64[b]	24.1[c]	23.1[cde]	147[cd]	134[c]	13.8[b]	133[b]	189[d]	156[bc]	37.1[a]
Manure	224	1680	0	2048	492[a]	96.0[a]	104[a]	7.94[a]	388[a]	146[a]	66.3[ef]	63.1[de]	3.18[b]	43.3[de]	558[bc]	190[b]	11.3[def]
Manure	56	420	0	788	91.5[bcd]	18.7[cd]	20.0[cd]	1.38[b]	71.5[cd]	48.4[bc]	83.8[def]	65.5[de]	18.2[b]	64.1[cd]	175[d]	113[c]	26.9[bc]
Boca	224	1680	0	2048	391[a]	45.3[b]	47.4[b]	2.14[b]	343[a]	88.6[ab]	126[cde]	114[cd]	12.1[b]	97.0[bc]	516[c]	186[b]	11.1[def]
Boca	56	420	0	788	65.9[bcd]	7.96[defg]	8.52[def]	0.56[b]	57.3[bc]	22.1[cde]	35.7[f]	30.8[e]	4.92[b]	31.2[efg]	193[de]	53.3[d]	12.7[de]
Pompano	224	1680	0	2048	111[bcd]	5.98[efg]	6.82[def]	0.84[b]	104[bc]	23.5[cde]	40.1[f]	34.6[e]	5.45[b]	39.3[de]	151[de]	62.8[d]	3.74[efgh]
Pompano	56	420	0	788	77.7[bcd]	2.24[fg]	2.65[f]	0.41[b]	75.0[bc]	11.3[efg]	46.5[ef]	34.3[e]	12.2[b]	33.1[ef]	124[de]	44.3[def]	10.5[defg]
Control	0	0	0	368	8.97[d]	0.99[fg]	1.16[f]	0.17[b]	7.80[c]	3.30[h]	29.2[f]	25.1[e]	4.02[b]	26.1[efgh]	38.1[e]	29.5[fg]	-
TSP	224	2370	1	2738	33.8[cd]	12.9[cdef]	13.4[cdef]	0.50[b]	20.5[c]	15.4[ef]	620[b]	524[b]	95.2[a]	448[a]	653[ab]	464[a]	19.6[cd]
TSP	56	1110	1	1478	15.6[d]	4.42[efg]	5.20[ef]	0.74[b]	10.4[c]	5.20[gh]	171[c]	162[c]	8.18[b]	140[b]	186[d]	146[bc]	13.2[de]
Manure	224	2370	1	2738	453[a]	47.2[a]	58.2[b]	11.0[a]	395[a]	90.3[ab]	51.4[ef]	38.8[e]	12.5[b]	23.6[fghi]	505[c]	114[c]	4.81[efgh]
Manure	56	1110	1	1478	48.9[bcd]	5.80[efg]	6.06[def]	0.27[b]	42.8[bc]	12.7[def]	51.1[ef]	30.8[e]	20.4[b]	34.3[ef]	100[de]	47.0[de]	4.23[efgh]
Boca	224	2370	1	2738	157[b]	22.6[c]	24.3[c]	1.74[b]	132[b]	35.2[bcd]	35.7[f]	30.8[e]	4.92[b]	28.9[efg]	192[d]	64.2[d]	2.71[fgh]
Boca	56	1110	1	1478	79.6[bcd]	6.69[defg]	7.06[def]	0.36[b]	72.6[bc]	15.1[de]	35.7[f]	23.9[e]	11.9[b]	30.3[efg]	115[de]	45.4[def]	4.09[efgh]
Pompano	224	2370	1	2738	137[bc]	4.16[efg]	4.94[ef]	0.78[b]	132[b]	15.5[de]	22.9[f]	21.1[e]	1.80[b]	15.9[hi]	160[de]	31.5[efg]	1.33[gh]
Pompano	56	1110	1	1478	41.4[cd]	1.38[fg]	3.17[f]	1.79[b]	38.2[bc]	4.67[fgh]	23.0[f]	21.0[e]	2.08[b]	19.1[ghi]	64.4[de]	23.8[gh]	2.14[fgh]
Control	0	690	1	1058	9.10[d]	0.38[g]	1.24[f]	0.86[b]	7.90[c]	0.91[i]	20.2[f]	18.5[e]	1.66[b]	16.4[i]	29.3[e]	17.3[h]	2.51[fgh]

†Total P ‡ Soluble reactive P §Total dissolved P ¶Dissolved organic P #Particulate P

††Bioavailable P (ISP) ‡‡Calculated as P added (source) + soil P (control) + WTR P (when applied)

§§Total BAP loss is sum of runoff and leachate BAP mass loss)

Phosphorus loss from treatments followed by the same letters (in the same column) are not different at $p = 0.05$ by Tukey test.

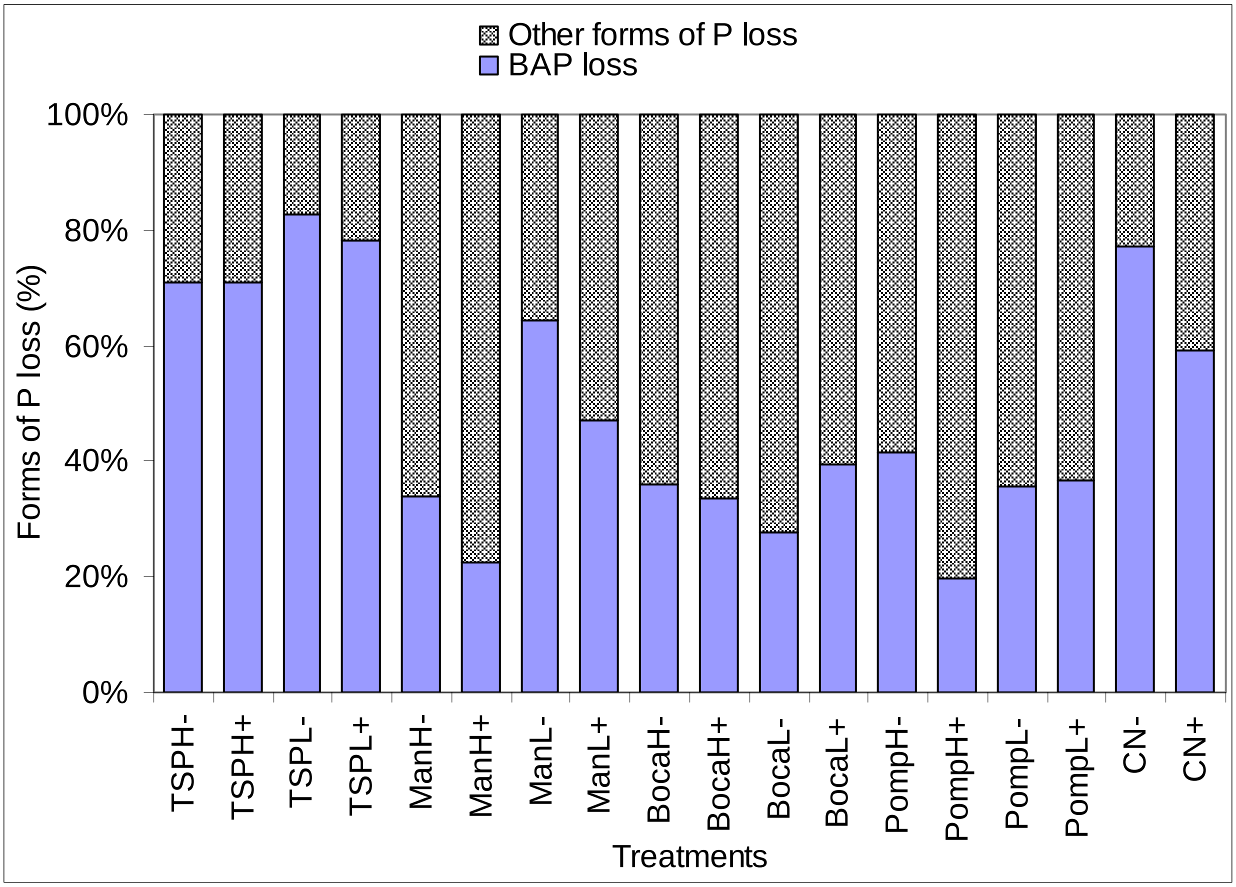


Figure 7-5. Proportions of total P loss as bioavailable P (BAP) from each treatment

Effect of P-Sources, P-Source Rates and WTR on BAP Losses

The BAP mass loss through runoff, leachate, and the Total BAP loss were all shown by ANOVA to be affected by the source of P, P-source rates and WTR (Table 7-2). The impacts of P-sources on runoff and leachate BAP loss were observed at N- and P-based rates. Greater BAP loss was observed at the two rates in the TSP treatments than in the organic source of P, reflecting the greater BAP concentrations of the high soluble-P mineral source than in the organic source of P (Table 7-3). However, the runoff BAP mass loss was similar in the TSP to the P loss in organic source of P at the P-based rate and even greater in the organic source of P than in the TSP at the N-based rate. The greater solubility of Boca Raton biosolids was reflected in its greater runoff and leachate BAP loss than observed in Pompano biosolids except in leachate at P-based rate. The greater solubility of manure than biosolids treatments is also consistent with the greater BAP mass loss observed in poultry manure treatment than in biosolids treatments especially at N-based in runoff and P-based in leachate.

Table 7-2. ANOVA table of the effect of P-source, P-source rates, and WTR on runoff bioavailable P (BAP), leachate BAP, and Total BAP mass losses.

Source of variation	Leachate-P loss	Runoff-P loss	Total P loss
P-Source	***	***	***
P-source rate	***	***	***
WTR	***	**	*
P-Source * P-source rate	***	***	***
P-Source *WTR	*	NS	***
P-source rate *WTR	**	NS	NS
P-Source * P-source rate *WTR	NS	NS	*

*** indicates significance at $p<0.001$
** indicates significance at $p<0.01$
* indicates significance at $p<0.05$

Application rate also affected the BAP losses. Greater BAP mass losses were observed at N-based than at P-based rates in the runoff from organic source of P treatments, and in leachate from TSP treatment (Table 7-3).

Runoff BAP losses were also reduced by WTR (Fig. 7-6). The runoff loss was greater in absence than in presence of WTR (Fig. 7-6). The impact of WTR was also observed in the leachate BAP mass loss. The WTR reduced leachate BAP loss in organic source of P treatments, but not in the TSP treatments (Table 7-4) and also at N-based rates but not at P-based rates (Table 7-4).

Table 7-3. Effects of P-source and P-source rates on runoff and leachates BAP mass loss (mg).

P loss	P-source	N-based rate	P-based rate	Contrasts N- vs. P-Based rate
Runoff	Poultry manure	119	30.6	**
	Boca Raton biosolids	61.9	18.6	**
	Pompano biosolids	19.5	7.98	*
	TSP	13.7	14.1	NS
	Contrasts			
	Organic vs. mineral source	***	NS	
	Manure vs. Biosolids	***	NS	
	Boca Raton vs. Pompano biosolids	**	*	
Leachate	Poultry manure	33.5	49.2	NS
	Boca Raton biosolids	62.9	30.7	NS
	Pompano biosolids	27.6	26.1	NS
	TSP	492	137	***
	Contrasts			
	Organic vs. mineral source	***	***	
	Manure vs. Biosolids	NS	*	
	Boca Raton vs. Pompano biosolids	*	NS	

*** indicates significance at $p<0.001$ by contrast
** indicates significance at $p<0.01$ by contrast
* indicates significance at $p<0.05$ by contrast
NS indicates nonsignificance at $p<0.05$ by contrast

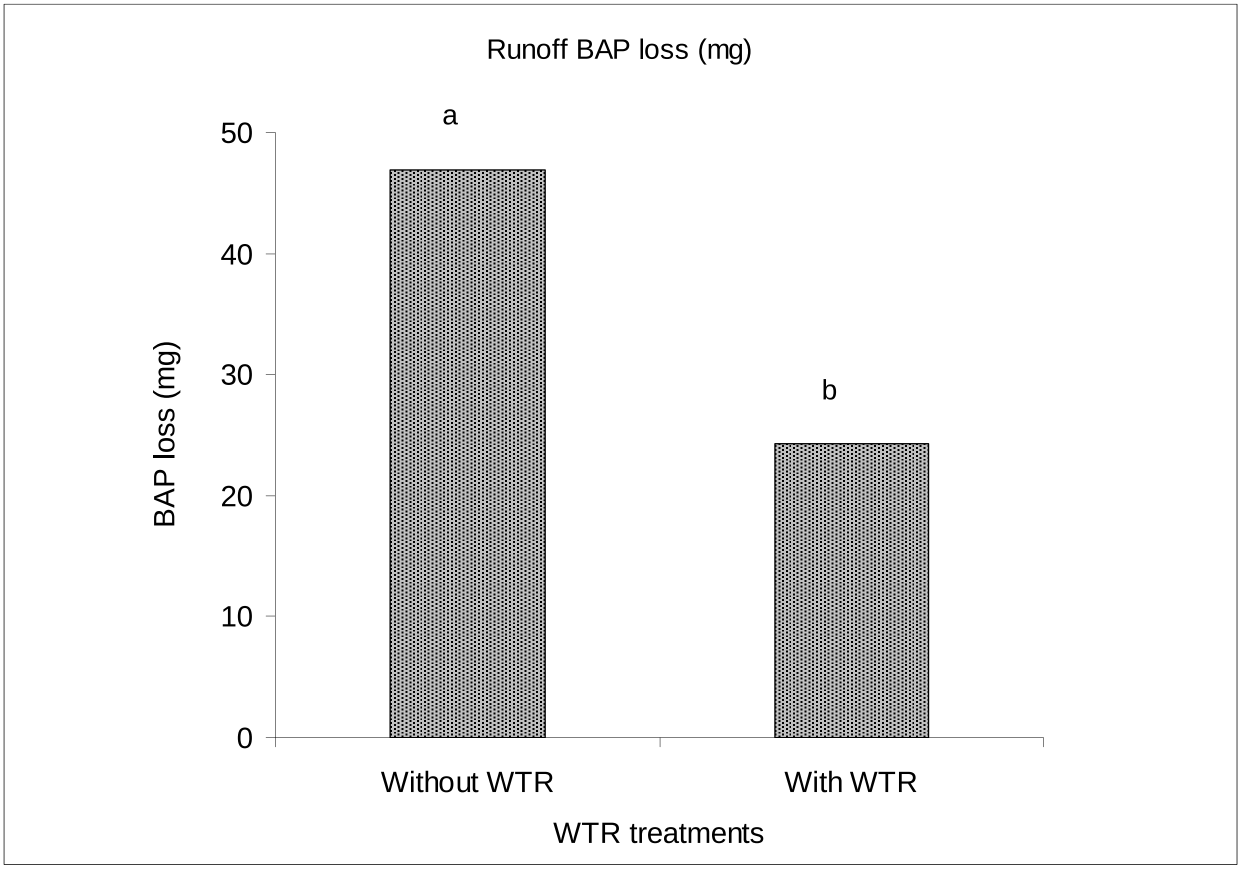


Figure 7-6. Effect of WTR on runoff BAP mass loss (Treatments with the same letters are not different at $p = 0.05$ by Tukey).

Most of the BAP loss from TSP was in leachate and unaffected by WTR addition on top of applied TSP. Mixing of the WTR with TSP and/or incorporation of both materials with soil would likely enhance WTR contact with, and retention of, soluble P and reduce the P loss (Elliott et al., 2002b; Novak and Watts, 2004; Dayton and Basta, 2005; Silveira et al., 2006). Others studies have shown WTR to reduce P losses in surface runoff (Gallimore et al., 1999; Basta and Storm 1997; Hausetein et al., 2000, Dayton et al., 2003) and in leachate when WTR and P-sources were co-incorporated with soil (Elliott et al., 2002; Novak and Watts, 2004). This study also shows that WTR, surface applied with P-sources, reduces BAP in both runoff and leachate.

Table 7-4. Effect of WTR and P-sources on leachate BAP mass loss (mg).

P-source	0% WTR	1% WTR	Contrasts 0% vs. 1% WTR
Poultry manure	53.7	28.9	**
Boca Raton biosolids	64.1	29.7	**
Pompano biosolids	36.2	17.5	***
TSP	334	295	NS
Contrasts			
Organic vs. mineral source	***	***	
Manure vs. Biosolids	NS	NS	
Boca Raton vs. Pompano biosolids	*	**	

*** indicates significance at $p<0.001$ by contrast
** indicates significance at $p<0.01$ by contrast
* indicates significance at $p<0.05$ by contrast
NS indicates nonsignificance at $p<0.05$ by contrast

Greater leachate BAP mass loss was also observed in the absence than in the presence of WTR at N-based rates and, thus, establishes the effectiveness of surface applied WTR at reducing leachate BAP loss (Table 7-5). The greater BAP losses observed at N-based than P-based rates in the absence of WTR was also eliminated when WTR is applied (Table 7-5). This supports the earlier observation that WTR addition can reduce and even eliminate the effect of excess P hazard associated with high P loads.

Analysis of variance showed that log transformed total masses of BAP loss were affected by P-sources, which was involved in a 3-way interaction with WTR and the application rates. The effects of all the treatments (including control) on Total mass of BAP loss was compared (Fig. 7-7). Total BAP loss (runoff + leachate) was greater at N-based, than at P-based, rates for all P-sources, except in Pompano biosolids treatment (Fig. 7-7). The minimal Total BAP loss in the moderate soluble-P Pompano biosolids could obscure the impact of application rate in the treatment.

Table 7-5. Effect of WTR and P-sources rate on leachate BAP mass loss (mg).

P-source rate	0% WTR	1% WTR	Contrasts 0% vs. 1% WTR
N-based	179	129	**
P-based	65.4	56.0	NS
Contrasts			
N-based vs. P-based	**	NS	

*** indicates significance at $p<0.001$ by contrast
** indicates significance at $p<0.01$ by contrast
* indicates significance at $p<0.05$ by contrast
NS indicates nonsignificance at $p<0.05$ by contrast

Also, P-sources affected the Total BAP mass loss, and the trends of absolute values of total BAP losses at each of the application rates suggested greater BAP losses from P-sources with greater PWEP values. The general order of total mass of BAP loss at the two rates (PWEP in parentheses) was: TSP (84%) > manure (18%) > Boca Raton biosolids (12%) > Pompano biosolids (4%). Thus, there are differences in the environmental hazards among the P-sources, and the tendency is for sources with low PWEP values to lose less BAP than high PWEP materials.

Total BAP mass losses were also smaller in the presence than in the absence of WTR for all organic sources of P at high rates, in manure and Pompano at low rate, and also in control treatments (Fig. 7-8). In the absence of WTR, total BAP losses from each of the organic sources applied at N-based rates were not greater than the P loss from TSP applied at a P-based rate. Thus, the hazards of excess P from applying the organic source of P at N-based rates is not greater than observed at P-based rates of mineral fertilizer. Also, total BAP loss at the high rate of Pompano biosolids was similar to BAP losses at the low rates of Boca Raton biosolids and manure treatments. This indicates hazards of excess P from applying the organic source of P at

N-based rates could be reduced to that observed at their P-based rates by applying moderate water soluble P-sources such as Pompano biosolids. Total BAP losses were further reduced by WTR application especially in the organic sources.

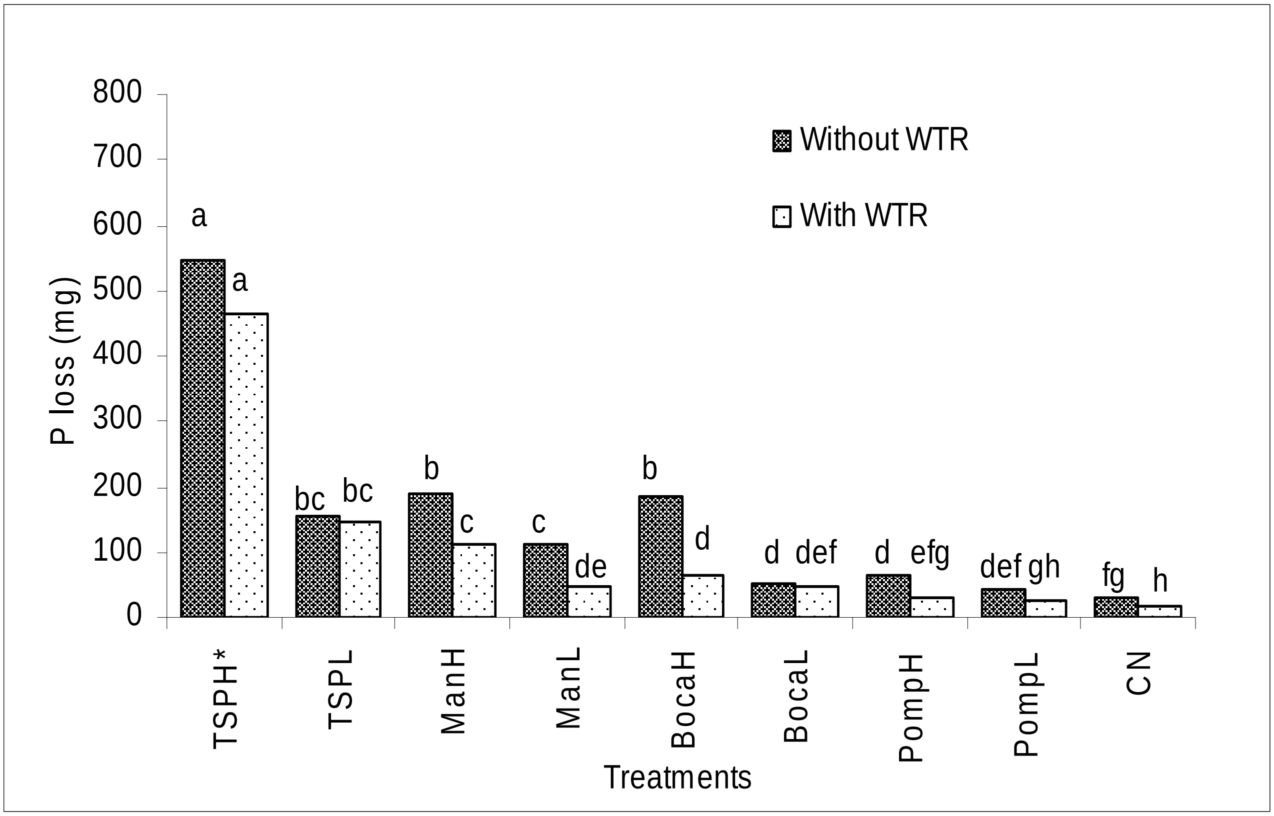


Figure 7-7. Total (runoff +leachate) mass of bioavailable P (BAP) lost during the three rain events. *Treatments ending with 'H' and 'L' represents high and low application rate of the P-sources, respectively. (Treatments with the same letters are not different at *p* = 0.05 by Tukey test)

Thus, this study indicates P loss in Florida sands amended at high rates of organic sources of P is smaller than at P-based rates of fertilizer P. Also the hazards of excess P at N-based rates could be managed to that observed at P-based rates by either applying moderate water soluble P-sources at N-based rate or co-applying the sources at high rates with WTR.

In the absence of WTR, ~35% of P applied was lost as BAP in TSP treatments and 12.7% in organic sources of P treatments (Table 7-1). In the presence of WTR, the BAP loss as a percentage of P applied was reduced to ~15% (TSP) and ~3% (organic sources of P). Masses of BAP lost in the presence of WTR is less than an averaged ~75% of BAP losses in the absence of WTR (Fig. 7-8).

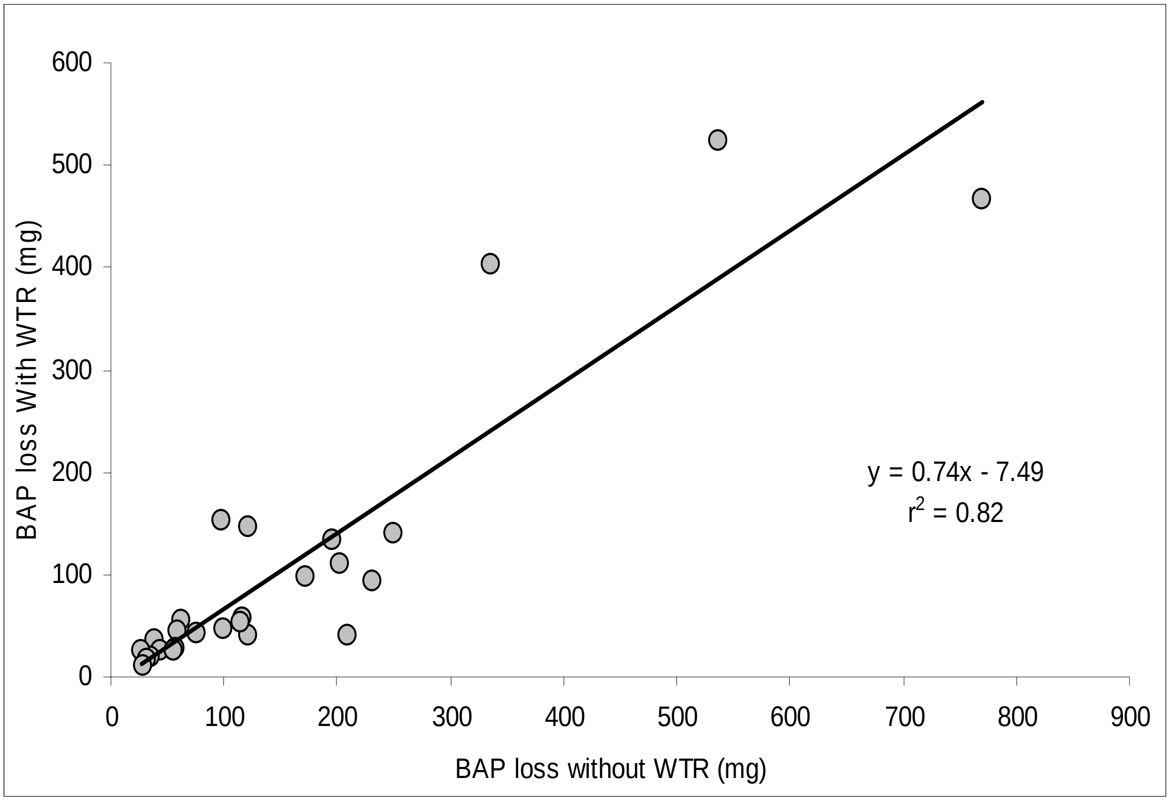


Figure 7-8. Total bioavailable P (BAP) loss with, versus without, WTR

Summary and Conclusions

Previous studies demonstrated the ability of WTR to reduce P loss in runoff. This study showed that both runoff and leachate P losses from surface applied P-sources can be reduced by surface applied WTR. The measured runoff P losses agree with previous studies that showed significant runoff P loss in the first rain event. Similarly, the first rainfall event resulted in greater leaching P losses than subsequent events. Leachate from the first rain event accounted for more than 70% of total P loss from TSP treatment and ~40% (depending on the P-source) from organic sources treatments during the three rainfall events. The BAP concentrations in leachates tracked well with WEP values: TSP (WEP = 175 g kg^{-1}) > Manure (WEP = 4.6 g kg^{-1}) ≈ Boca Raton biosolids (WEP = 5.5 g kg^{-1}) > Pompano biosolids (WEP = 1.2 g kg^{-1}).

The masses of TP losses from TSP treatments were greater in leachate (147 – 746 mg) than in runoff (16 – 42 mg) from the sandy soil. However, runoff TP losses were greater in the organic sources (41 - 492 mg) than in the TSP (16 – 42 mg) treatments due to greater particulate P (which dominated the runoff P losses) in organic source than the TSP treatments. The masses of BAP losses in TSP treatments were substantially greater in leachate (133 – 536 mg) than in runoff (5 – 23 mg).

In addition to the reported ability of WTR to reduce P in surface runoff or in leachate when incorporated with the soil, the study shows that surface applied WTR reduced P losses in leachates as well as in runoff. The masses of BAP and TP loss were similarly affected by the P-sources and followed the same trend as PWEP of the sources: TSP > Manure > Boca Raton biosolids > Pompano biosolids.

The trends of the TP losses agree with the flow-weighted BAP concentrations and show that the P hazards associated with applying organic sources of P at N-based rates are smaller than for fertilizer P applied at P-based rates. The study suggests that environmental P hazards associated with high application rates (N-based) of P materials can be managed by either applying the sources with WTR, or by using a moderate water soluble P-sources (e.g., Pompano biosolids). The total BAP mass losses at the N-based rate of TSP were greater than at the P-based rate. Most of the loss was in leachate and was unaffected by WTR placed on top of applied TSP. Mixing of the WTR with TSP and/or incorporation of both materials with soil would likely enhance WTR retention of soluble P and reduce the BAP loss.

CHAPTER 8
A METHODOLOGY TO ACCOUNT FOR P RELEASE POTENTIAL FROM DIFFERENT SOURCES OF P: FLORIDA P INDEX AS A CASE STUDY

Introduction

Concerns over impacts of agricultural watersheds on water quality degradation resulting from accelerated eutrophication have elicited various initiatives. The national initiatives include the Unified Strategy for Animal Feeding Operation issued by USDA and USEPA (USEPA, 1999), which requires each state NRCS to address P in nutrient management practice standards (Code 590). The three strategies outlined in code 590 for managing P in agricultural operations are: (1) soil test crop response strategy, (2) environmental soil P threshold strategy, and (3) P Index. Most states, including Florida, opted for the P Indexing tool (P Index), which considers multiple landscape and management factors demonstrated to affect P loss to water bodies. The P Index addresses both P-source and transport factors, as P loss requires coexistence of labile P-source and viable transport pathway.

The original P Index contained five 'source' and four 'transport' factors, designed to identify vulnerable sites where P loss reduction should be focused (Lemunyon and Gilbert, 1993). The draft Florida P Index similarly describes the relative risk of P movement from a given field using nine variables that are known to govern P losses (Graetz et al., 2004). One of the nine variables identified to affect P losses is the P-source, which is assigned a weighting coefficient to distinguish P-source lability, based on professional judgments of the scientists developing the approach.

The solubility, bioavailability, and transport potential of P varies among biosolids, manures, and fertilizer types (Brandt et al., 2004; Leytem et al., 2004; Elliott et al., 2005). This fact is not well appreciated in most state P indices being developed because variations in P losses due to P-sources are not well accounted for. The draft Florida P Index currently uses a single coefficient (0.05) for both P-fertilizers and all kinds of manures, and a single value (0.015) for all kinds of biosolids (Graetz et al., 2004). Assigning a lower coefficient to biosolids than fertilizer and manures is based on evidence that the Fe and Al contents of biosolids affect P solubility in biosolids-amended soils (Elliott et al., 2002a). However, fundamental differences in the behavior of P-sources warrant additional differentiation of P-sources. Biosolids, for example, vary in Fe and Al concentrations and, hence, P solubility depending on method of production (O'Connor et al., 2004). Biosolids produced via biological P removal (BPR) process can mimic fertilizer P with regards to P lability. Hence, P loss is expected to be greater in BPR biosolids amended soils than in soils amended with biosolids with high Fe and Al concentrations, or in BPR biosolids supplemented with Al. Biosolids vary widely in susceptibility to P solubilization by water (Brandt et al., 2004), and loss in surface runoff and subsurface drainage (Penn and Sims, 2002; Elliott et al., 2002a; Sims et al., 2003; Elliott et al., 2005). Similarly, manures vary in P form and solubility depending on animal source, animal diets, storage and handling practices (Barnett, 1994; Leinweber, 1996; Kleinman et al., 2005; Wolf et al., 2005; Vadas and Kleinman, 2006). Sharpley and Moyer (2000) showed that P forms and P release to leachates vary widely with different manure sources.

The wide variability in P-source solubility has resulted in the suggestion of continuous, rather than discrete, coefficients to account for P availability of the P-sources (Elliott et al., 2006). Elliott et al. (2006) recently proposed a more refined algorithm for the estimation of P-source coefficients (PSC) based on correlations of runoff dissolved P and WEP values (of multiple applied manures and biosolids) generated from seven published rainfall simulation studies. However, the PSC values developed exclusively on runoff P loss data may be inadequate in Florida and other coastal plain soils where leaching losses of P can be significant. Thus, it was hypothesized that there exist better coefficients to account for P-source potential to P loss in Florida sands with significant leachate P loss. The objective of this study was to determine a methodology that could measure the impacts of P-sources on P losses in Florida soils in a rainfall simulation study.

Materials and Methods

Data from a rainfall simulation experiment carried out as prescribed in the National Phosphorus Research Project indoor runoff box protocol, but with leaching and runoff P quantified was used for the study. The details of the rainfall simulation procedures and analysis of runoff and leachates are given in Chapter 7. Only data for treatments without WTR (four P-sources at two rates and a control) were used in this study. Thus, the experiment could be described as a 4 by 2 factorial experiment in randomized complete block design.

The rainfall simulation results were compared with data from a glasshouse column leaching study that use two Florida soils (Elliott et al., 2002a) to validate the findings. The glasshouse study involved 126 columns packed with treated 15 cm of A-horizons of either the moderate P-sorbing Candler soil (hyperthermic, uncoated Typic Quartzipsamments) or the low P-sorbing Immokalee series, overlying 28 cm of E-horizon of the Myakka series. Each of the top soils was treated with ten P-sources (including 8 biosolids, poultry manure, and TSP), and planted with bahiagrass. Columns were leached after each of four grass harvests, and total P in the leachates over the 4 month growing season were determined. The water extractable P (WEP), total P (TP), and other properties of the P-sources were also determined. Details of the experiment are given in Elliott et al. (2002a). The column study data are suitable to validate the result from rainfall simulation study because more P-sources (ten) and soils (2) were used than in the rainfall simulation study. The leaching study, also in a different way account for the total P loss (as leachate without runoff), while the modified rainfall simulation study accounted for total P loss as sum of runoff and leachates P losses.

Statistical Analysis

Normal probability plots and residuals of the data were examined to ensure the data satisfied the assumptions of normality, constant variance and independence. Where the assumptions were violated, appropriate transformations were applied using Box Cox transformation (SAS Institute, 1999) to normalize the runoff and leachate P concentrations and P loss data, and stabilize the variance. Analysis of Variance (ANOVA) was performed on the various forms of runoff and leachate P loss (concentrations and masses) data (or the transformed data) using PROC GLM to determine significance treatment effects (SAS Institute, 1999). When significance was indicated by ANOVA, the Tukey method was used to separate the means at $\alpha \leq 0.05$. Simple linear regressions (ordinary least square) were used to model the relationship between TP loss and P-source rates (or P-source adjusted rates) using PROC REG in SAS (SAS Institute, 1999). Correlations of the P-source coefficients with the P losses were obtained using PROC CORR in SAS (SAS Institute, 1999).

Results and Discussion

Runoff and Leachate P as Affected by P-Sources

Masses of TP loss in runoff and leachate and their sum are shown in Table 8-1. The masses of total P loss in the runoff are similar for the organic source of P treatments at each application rate, but greater than runoff P loss in TSP treatments at the two rates. However, the greater leachate P losses in TSP treatments (Table 8-1) resulted in greater total (runoff plus leachate) masses of P loss (TP).

Table 8-1. Mean masses (n = 3) of P lost in runoff and leachates during rainfall simulation experiment

P-source	P-source Rate (kg ha^{-1})	Runoff P loss	Leachate P loss	†Total P loss	‡ Total BAP loss	Percentage of applied P lost as BAP (%)
		<---------------- mg------------------------->				
TSP	224	27.3 ^{c}	746 ^{a}	774 ^{a}	548 ^{a}	32.6 ^{a}
	56	41.7 ^{c}	147 ^{b}	189 ^{bc}	156 ^{b}	37.1 ^{a}
Poultry manure	224	492 ^{a}	66.3 ^{bcd}	558 ^{a}	190 ^{b}	11.3 ^{b}
	56	91.5 ^{abc}	83.8 ^{bcd}	175 ^{c}	113 ^{bc}	26.9 ^{a}
Boca Raton biosolids	224	391 ^{ab}	126 ^{bc}	516 ^{ab}	186 ^{b}	11.1 ^{b}
	56	65.9 ^{bc}	35.7 ^{cd}	193 ^{c}	53.3 ^{cd}	12.7 ^{b}
Pompano biosolids	224	111 ^{abc}	40.1 ^{cd}	151 ^{c}	62.8 ^{cd}	3.74 ^{b}
	56	77.7 ^{abc}	46.5 ^{d}	124 ^{c}	44.3 ^{d}	10.5 ^{b}

†Total P loss is sum of runoff and leachate P mass loss.
‡Total bioavailable P (BAP) loss is the sum of runoff and leachate BAP masses lost.
Phosphorus loss from treatments followed by the same letters (in the same column) are not different at $p = 0.05$ by Tukey (statistical analysis based on log-transformed data)

The TP losses in manure and Boca Raton biosolids treatments at the high P rate were similar to the losses in TSP treatments, but greater than losses at low P rates of all P-sources and than losses from both rates of the Pompano biosolids treatments. Thus, the TP loss from moderate water soluble P Pompano biosolids (even at the N-based application rate) was similar to losses for other sources applied at P-based rates.

Similar (or smaller) BAP loss occurred in Pompano biosolids treatments at high P loads than at low P loads of the other P-sources (Fig. 8-1). At the high P rate, greater masses of total

BAP loss (leaching plus runoff) were observed in TSP treatments than in manure and Boca Raton biosolids treatments. This is expected of the high soluble inorganic source of P. The organic sources generally contain lower concentrations of TP and soluble P compared to the mineral P-source.

Similar to TP loss data, BAP losses from both manure and Boca Raton biosolids treatments were greater than in Pompano biosolids treatment. Thus, contrary to the similar coefficients assigned in the draft Florida P Index to fertilizer and manure, the BAP losses from TSP treatments were greater than from manure treatments. Also, greater BAP losses were observed in the high water soluble P Boca Raton biosolids treatment than in moderate water soluble P Pompano biosolids treatment. In addition, contrary to the different assigned coefficients in the draft Florida P Index, similar P losses were observed in manure and Boca Raton biosolids treatment. Thus P losses from some biosolids, especially high water soluble P biosolids, were comparable to the greater P losses expected from manures treatments.

Total BAP losses of the 8 treatments (4 P-sources, each at 2 rates) varied as: TSP (at high rate) > manure and Boca Raton biosolids (at high rate) ≈ TSP (at low rate) ≈ Manure (at low rate) > Boca Raton biosolids (at low rates) ≈ Pompano biosolids (at high rate) ≈ Pompano biosolids (at low rate) ≈ control (Fig. 8-1c). The P hazard at the N-based rate of the organic sources was about the same as the P-based rate of TSP, and the P hazard of the moderate soluble P biosolids applied at the N-based rate was no more than the P-based rate of other P-sources.

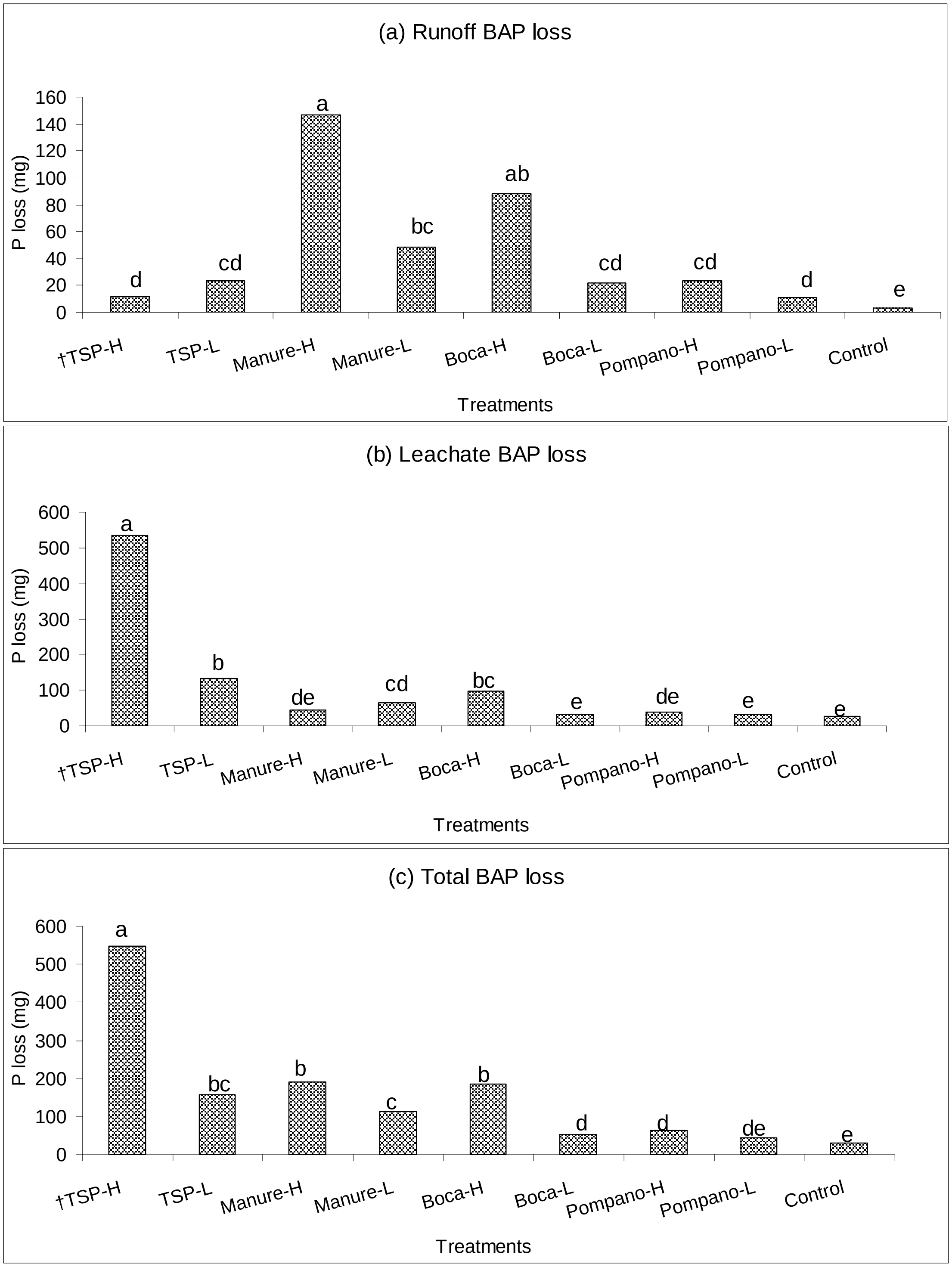


Figure 8-1. Bioavailable P (BAP) lost in (a) runoff, (b) leachate, and (c) total (runoff + leachate) as affected by the P-sources at the two application rates. (Treatments followed by the same letters are not different at $p = 0.05$ by Tukey test; †Treatments with labels ending in "H" and "L" indicate high and low application rates of the P-source, respectively)

Relative P Losses and P-source Coefficients

The regressions of total mass of BAP loss as a function of application rate for each of the four P-sources are shown in Table 8-2. Loading rate accounted for at least 70% of the variability ($r^2 > 0.7$, CV < 60%) in mass of BAP loss from any of the P-sources. However, the coefficients of determination (r^2) and the slopes varied with the different organic sources of P, indicating that equal P loadings result in varying P loss for different P-sources. Generally, the total mass of BAP loss increased with P load for all sources (positive slope).

Table 8-2. Regressions of total bioavailable P (BAP) loss with P applied for each P-source (at zero intercept).

P-source	Slope	r^2	CV (%)	*p*-value
TSP	2.47	0.90	48	<0.0001
Poultry manure	0.92	0.90	40	<0.0001
Boca Raton biosolids	0.84	0.92	40	<0.0001
Pompano biosolids	0.31	0.74	57	0.0014

The rate of increase in BAP loss per unit increase in P load was ~2.5 for TSP, ~0.9 for manure, 0.8 for Boca Raton biosolids, and 0.3 for Pompano biosolids. The BAP loss from soils treated with Boca Raton biosolids was about three times greater than the loss from soils treated with Pompano biosolids for each unit increase in applied P. The BAP loss from soil amended with Pompano biosolids at the high P rate (224 kg P ha^{-1}) was similar to the BAP loss from Boca Raton biosolids amended soil at the low P rate (56 kg P ha^{-1}). The P loss from soil amended with TSP was ~2.5 times greater than the P loss from manure. The results are not consistent with the draft Florida P Index that assigns the same 0.05 coefficient for fertilizer and manures and 0.015

for all biosolids. However, the results agree with the assumed greater lability of manure-P than biosolids-P in the draft Florida P Index. The BAP losses from manure treatments were greater than from Boca Raton and Pompano biosolids treatments at either application rate.

Parameters that could account for variable P losses include PWEP, WEP, WEP-based PSC proposed by Elliott et al. (2006), and the P-source coefficients in the draft Florida P Index (FPSC). The ranking of total (runoff + leachate) masses of TP and BAP losses at the two application rates agree with the ranking of the PWEP values of the sources, (PWEP values in parentheses): TSP (84%) > manure (18%) > Boca Raton biosolids (12%) > Pompano biosolids (4%) (Table 8-3). The WEP value of manure (4.57 mg kg^{-1}) was less than the value for Boca Raton biosolids (5.52 mg kg^{-1}), but P losses (BAP and TP) were greater in manure treatments than in the Boca Raton biosolids treatments. Thus, values of PWEP could be superior to WEP as indices of organic source of P solubility and as predictors of P loss.

Table 8-3. Total P (TP) and bioavailable P (BAP) losses and some indices of the P-sources solubility

Source	<---Possible P-source coefficients-->				Total BAP loss (mg)		Total P loss (mg)	
	WEP (g kg^{-1})	PWEP[¶] (%)	FPSC[§]	PSC[†]	High rate	Low rate	High rate	Low rate
TSP	175	84	0.05	1.00 (1.0)	548 [a]	156 [a]	774 [a]	189 [a]
Poultry Manure	4.57	18	0.05	0.46 (0.9)	190 [b]	113 [a]	558 [b]	175 [a]
Boca Raton biosolids	5.52	11	0.015	0.55 (0.8)	186 [b]	53.2 [b]	516 [b]	193 [a]
Pompano biosolids	1.16	4	0.015	0.12 (0.4)	62.8 [c]	44.3 [b]	151 [c]	124 [a]

[†]P-source coefficients calculated from the P-source WEP (g kg^{-1}) as: $PSC = 0.102 \times WEP^{0.99}$ (Elliott et al., 2006). Values in the parenthesis are the corresponding Mid-Atlantic region PSC for the sources.
[‡]P-source coefficients from the draft Florida P Index (Graetz et al., 2004).
[§]Percentage water extractable P
Phosphorus loss from treatments followed by the same letters (in the same column) are not different at $p = 0.05$ by Tukey (statistical analysis based on log-transformed data)

The PSC values related well with the rankings of mass of P losses (BAP and TP), especially for biosolids (Table 8-3). The PSC is a characteristic of the P-source developed in Pennsylvania as an indicator of relative solubility and accounts for the proportion of total P applied to a field that is potentially subject to loss with drainage water (Weld et al., 2000; Coale et al., 2005). The PSC is calculated from an empirical relationship using WEP values (g kg^{-1}) of the sources as:

$$PSC = 0.102 \times WEP^{0.99}$$

The relationship was derived from correlations of runoff dissolved P from several studies with the P-source WEP values (Elliott et al., 2006). The masses of TP and BAP losses for the various P-sources are given along with the PSC values calculated from the P-source WEP values and other indices in Table 8-3.

The Mid-Atlantic region PSC values for use in P Index site evaluation are expressed on a relative scale from zero to one: 1.0 (inorganic P fertilizer and swine manure), 0.8 (other manures, BPR biosolids) 0.5 (alum-treated manure) and 0.4 (all other biosolids) (Coale et al., 2005). The Pennsylvania PSC values (related to TSP) are 1.0 (swine slurry), 0.9 [poultry (layer), turkey, duck, and dairy (liquid) manure], 0.8 [poultry (broiler), beef and dairy (bedded pack) manure and BPR biosolids], 0.4 (alkaline stabilized biosolids), 0.3 (conventionally stabilized and composted biosolids) and 0.2 (heat-dried and advanced-alkaline stabilized biosolids).

The relationships between the total BAP losses and the various indices of P-source solubility were modeled. Masses of BAP losses correlated better with PWEP values than with the PSC and FPSC values especially in the Florida sand, where leaching is an issue (Table 8-4). Regression of masses of total BAP loss with application rates gave poor relationships ($r^2 < 0.30$) with high variability (CV = 95%, Table 8-5). The poor relationship indicates that application rate alone is not sufficient to account for P losses where different P-sources are applied. When the differences in solubility of the P-sources were accounted for by multiplying the application rates with PWEP, PSC, or FPSC values, the relationships improved ($r^2 > 0.50$). Elliott et al. (2005) also reported improved prediction of runoff P concentrations when application rates were adjusted with PSC values (rates multiplied by PSC values). However, accounting for P-source solubility with PWEP values resulted in better coefficients of determination ($r^2 = 0.81$) and lower variability (CV = 49%) than when FPSC ($r^2 = 0.54$, CV = 76%) or PSC values ($r^2 = 0.77$, CV = 54%) were used. The data indicate not only the need for a coefficient to account for difference in P-source solubility, but that PWEP is superior to PSC and FPSC, especially in cases where leachate P losses are significant, as in Florida soils.

Table 8-4. Pearson correlation coefficients and *p*-values between P loss (bioavailable P (BAP) and total P (TP)) and various P-source solubility coefficients.

Form of P loss			Rate	WEP	§FPSC	¶PSC	#PWEP
Based on rainfall simulation experiment	BAP (Immokalee soil)	Runoff	0.501†	-0.266	0.135	0.048	-0.153
			0.007‡	0.1802	0.087	0.812	0.445
		Leachate	0.367	0.714	0.439	0.641	0.711
			0.0596	<0.0001	0.008	0.0003	<0.0001
		Total	0.517	0.650	0.542	0.665	0.679
			0.0057	0.0002	0.004	0.0002	0.0001
Based on data from Elliott et al., 2002	Total P (Candler soil)	Leachate	0.258	0.694	0.476	0.445	0.635
			0.3016	0.0014	0.046	0.064	0.005
	Total P (Immokalee soil)	Leachate	0.3610	0.679	0.466	0.648	0.709
			0.141	0.0019	0.052	0.004	0.001

†Correlation coefficient (r)
‡*p*-value
§P-source coefficients from Florida P Index (Graetz et al., 2004).
¶P-source coefficients calculated from the P-source WEP (g kg^{-1}) (Elliott et al., 2006).
#Percentage water extractable P

Table 8-5. Regressions of total bioavailable P (BAP) mass loss with P applied (and FPSC†, PWEP‡ and PSC§ adjusted P applied) for all the P-sources in rainfall simulation experiment.

Independent variables	Intercept	Slope	r^2	CV (%)	*p*-value
Rate	36.6	0.94	0.27	95	0.0001
Rate*FPSC	30.9	30.3	0.54	76	<0.0001
Rate*PSC	13.5	2.11	0.77	54	<0.0001
Rate*PWEP	57.2	0.03	0.81	49	<0.0001

† P-source coefficients from the draft Florida P Index (Graetz et al., 2004).
‡ Percentage water extractable P
§ P-source coefficients calculated from the P-source WEP values (g kg^{-1}) (Elliott et al., 2006).

The best regression of P loss with PWEP adjusted rates was also obtained for data from another study (Elliott et al., 2002a) that focused on P leaching. The study used another Florida soil (Candler series) in addition to the Immokalee soil used in the rainfall simulation study (Table 8-6). The predictions for the two soils were better when application rates were adjusted with PWEP values (r^2 = 0.85, 0.79 and CV = 59, 86%) than with FPSC values (r^2 = 0.72, 0.36 and CV = 81, 150%) and PSC values (r^2 = 0.74, 0.56 and CV = 79, 123%).

Table 8-6. Regressions of mass of P loss with P applied and FPSC†, PWEP‡ and PSC§-adjusted P loads for P-sources used in a leaching study with two Florida soils (data from Elliott et al., 2002a used).

Independent variables	<-----------Candler soil---------->			<---------Immokalee soil --------->		
	r^2	CV (%)	*p*-value	r^2	CV (%)	*p*-value
Rate	0.14	142	0.148	0.03	183	0.5270
Rate*FPSC	0.72	81	<0.0001	0.36	150	0.0146
Rate*PSC	0.74	79	<0.0001	0.56	123	0.0008
Rate*PWEP	0.85	59	<0.0001	0.79	86	<0.0001

† P-source coefficients from the draft Florida P Index (Graetz et al., 2004).
‡ Percentage water extractable P
§ P-source coefficients calculated from the P-source WEP values (g kg^{-1}) (Elliott et al., 2006).

Using data from the rainfall simulation study, P Index scores were calculated for the four P-sources at each of the two rates (P-based and N-based) assuming similar transport variables, FIVs, and AM, with no waste water applied. The scores were calculated using the draft Florida P Index worksheet, and P-sources accounted for by the three different approaches (PSC, FPSC, and PWEP) as in Table 8-7.

Ranking of BAP losses was more consistent with P Index score obtained using PWEP, than with either PSC- or FPSC-based P Index scores. The observed Total BAP losses were regressed with the calculated P Index scores obtained using each of the three approaches (PSC, FPSC, and PWEP) as in Fig. 8-2. Regression also show P Index scores obtained using PWEP better estimated BAP loss, than scores obtained using either PSC or FPSC (Fig. 8-2).

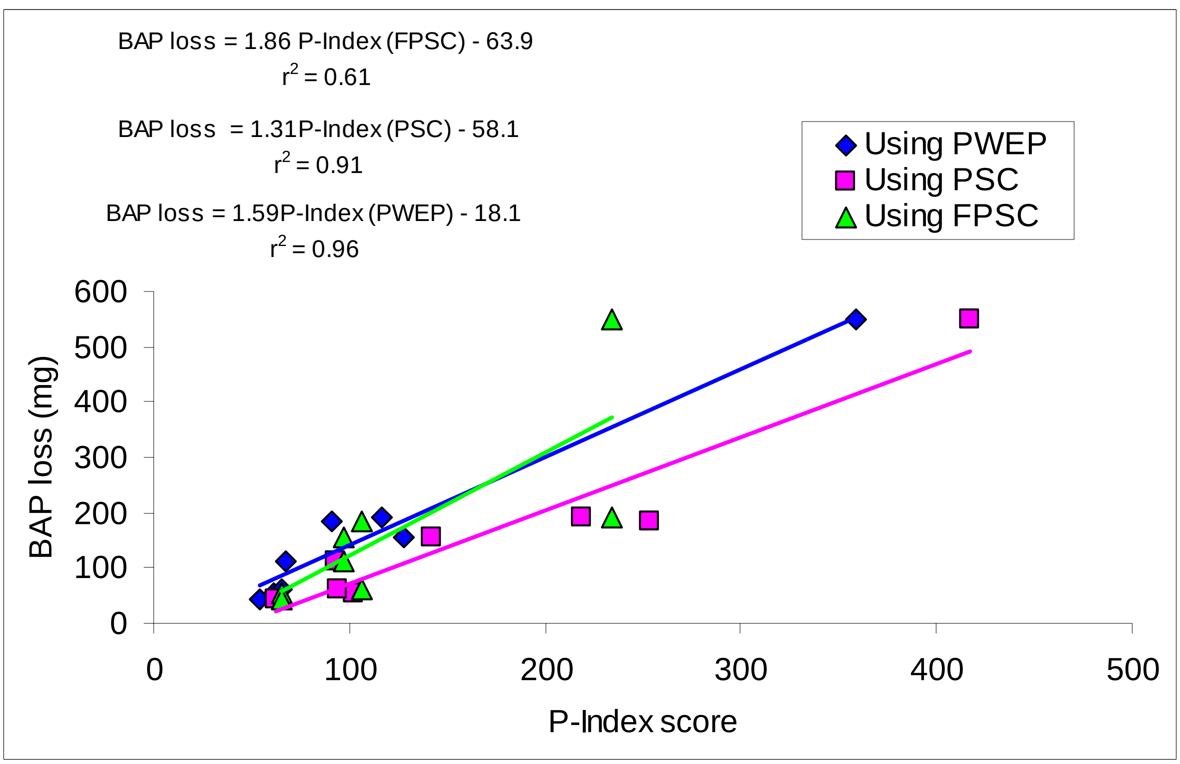


Figure 8-2. Regression of bioavailable P (BAP) loss with P Index score obtained using varying measures of coefficients (Percentage water extractable P (PWEP); P-source coefficients (PSC); Florida P Index source coefficients (FPSC)).

Table 8-7. Trends of draft Florida P Index scores (using different P-source coefficients; FPSC[†], PWEP[‡] and PSC[§]) and bioavailable P loss from the four P-sources at two P rates during the rainfall simulation study

Factors	Variable	<-Manure->		Boca Raton biosolids		<Pompano biosolids>		<--TSP---->	
		P-based	N-based	P-based	N-based	P-based	N-based	P-based	N-based
P-source	P rate (lb P_2O_5 acre^{-1})	115	458	115	458	115	458	115	458
	FPSC	0.05	0.05	0.015	0.015	0.015	0.015	0.05	0.05
	PSC	0.046	0.046	0.055	0.055	0.012	0.012	0.10	0.10
	PWEP	0.018	0.018	0.011	0.011	0.004	0.004	0.084	0.084
	P-source multiplier (FPSC)	5.7	22.9	1.7	6.9	1.7	6.9	5.7	22.9
	P-source multiplier (PSC)	5.3	21.0	6.3	25.4	1.4	5.4	11.5	45.8
	P-source multiplier (PWEP)	2.1	8.2	1.3	5.0	0.5	1.8	9.6	38.5
	FIV@ 7ppm M-1P	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Application method	6	6	6	6	6	6	6	6
	Waste water (not applied)	0	0	0	0	0	0	0	0
Transport	Soil Erosion	1	1	1	1	1	1	1	1
	Runoff potential	2	2	2	2	2	2	2	2
	Leaching potential	4	4	4	4	4	4	4	4
	Potential to reach water body	1	1	1	1	1	1	1	1
P Index score using FPSC		97	234	65	106	65	106	97	234
P Index score using PSC		93	219	102	254	62	94	142	417
P Index score using PWEP		67	117	61	91	54	65	128	359
Bioavailable P loss (mg)		113	190	53	186	44	63	156	549

[†]P-source coefficients from the draft Florida P Index (Graetz et al., 2004).
[‡]Percentage water extractable P
[§]P-source coefficients calculated from the P-source WEP values (g kg^{-1}) (Elliott et al., 2006).

To enhance comparing the wide spectrum of P-source solubilities, PWEP, as a continuous coefficient, could be used. The PWEP could be converted to a P-source coefficient in the range of 0 to 0.10 (as in FPSC) by multiplying the PWEP by 10^{-3}. Thus, TSP with PWEP of 85%

would be assigned a source coefficient of 0.085. The PWEP can be calculated or taken as default values from the average of the PWEP values for different P-sources reported by Brandt et al. (2004) as in Table 8-8. The proposed PWEP-based PSC values would substitute for the coefficients (0.05, 0.015 and 0.1) in the "P application source and rate" section of the draft Florida P Index. This approach not only adequately accounts for differences in the P-sources, but also satisfies calls for the use of continuous coefficients to account for the P-source impacts (Elliott et al., 2006).

Table 8-8. Percentage water extractable P (PWEP) values of some P-sources (calculated using data from Brandt et al., 2004) and the corresponding P-source coefficients based on the PWEP values at the 0 – 0.1 range in the draft P Index.

P-source	Type of P-source	§ FPSC	† PWEP (%)	‡ PWEP-based source coefficient (PWEP-SC)
Biosolids	Aerobically digested cake	0.015	2.75	0.003
	Anaerobically digested cake	0.015	2.21	0.002
	Biological P removal	0.015	13.9	0.013
	Alkaline stabilized cake	0.015	7.39	0.007
	Composted	0.015	3.04	0.003
	Heat dried	0.015	0.48	0.0005
	BPR heat dried	0.015	11.3	0.011
	BPR N-vitro	0.015	0.21	0.0002
	Unstabilized	0.015	10.4	0.010
Manures	Dairy manure	0.050	51.8	0.052
	Poultry manure (Layer)	0.050	20.4	0.020
	Poultry manure (Broiler)	0.050	20.9	0.021
Fertilizer	TSP	0.050	85.2	0.085

† Based on average of PWEP values obtained from Brandt et al., 2004
‡ Based on the PWEP and the 0 - 0.1 range of P-source coefficients in the draft Florida P Index (Graetz et al., 2004)
§ P-source coefficients from Florida P Index (Graetz et al., 2004).

Summary and Conclusions

Land application of different P-sources resulted in varying environmental P losses because of differences in P-source water solubility. The three coefficients suggested in the draft Florida P Index (coefficient = 0.05 for fertilizer and manure, 0.015 for biosolids, and 0.10 for waste water) are insufficient to account for the wide variability in organic sources of P solubility. Masses of both TP and BAP losses from various P-sources applied at N-based and P-based rates followed similar trends with P-source percentage water extractable P (PWEP) values in studies that accounted for leachate P loss. The trend of the P losses (PWEP values in parentheses) was: TSP (84%) > manure (18%) > Boca Raton biosolids (12%) > Pompano biosolids (4%). Regressions of BAP loss with application rate ($r^2 = 0.27$) were improved by accounting for P-source solubility differences with: the Florida P Index coefficients ($r^2 = 0.54$), P-source coefficients (PSC) values suggested by Elliott et al. (2006) ($r^2 = 0.77$), and PWEP ($r^2 = 0.81$).

Similar improvements in the P loss model with PWEP and other coefficients were observed for data from another study that measured P leached from two Florida soils amended with eight biosolids, poultry manure and TSP. The r^2 values observed in the regressions of P lost with P application rate were improved by using coefficients in the draft Florida P Index and PSC, but the improvement was better still with PWEP values. Use of coefficients based on PWEP of the P-source is suggested as an alternative to coefficients currently used in the draft Florida P Index, and default values for PWEP-based coefficients are suggested.

CHAPTER 9
FIELD VALIDATION OF ENVIRONMENTAL IMPACTS OF LAND APPLIED P-SOURCES AND WATER TREATMENT RESIDUAL (WTR)

Introduction

Phosphorus added in excess of forage uptake and a soil's P sorption capacity can leach to shallow groundwaters (Liu et al., 1997). This is particularly important in Florida low P- sorbing sands. The dominant soil group in Florida, Spodosols, is characterized by high water tables located between the Bh and the A horizons, especially during the summer rainy season. Phosphorus contamination of the shallow groundwaters can be conveyed to surface waters via drainage ditches (Burgoa et al., 1991; Mansell et al., 1991). A chemical fractionation study by Graetz and Nair (1995) indicated that about 80% of total P (TP) in the A-horizon of spodosols is leachable. Variables associated with P-sources that affect the amounts of P leached are the composition of the sources, source application rates, and the use of P-sorbing materials such as water treatment residuals (WTR).

Studies have indicated the sorption properties of low P sorbing soils can be improved by applying WTR (Peters and Basta, 1996; Basta and Storm, 1997; O'Connor and Elliott, 2001; O'Connor et al., 2002a; Elliott et al., 2002b; Elliott et al., 2005; Novak and Watts, 2005). Reductions in P concentrations in runoff occur following surface application of WTR (Peters and Basta, 1996; Basta and Storm, 1997; Dayton et al., 2003), and of P in leachates when WTR is incorporated into the soil (Elliott et al., 2002b; O'Connor et al., 2002a; Novak and Watts, 2004; Dayton and Basta, 2005). Surface co-application of the P-sources and WTR reduced both leachate and runoff P concentrations in a rainfall simulation experiment (Chapter 7).

Most studies that evaluated impacts of the P-sources and WTR additions on soluble P in Florida soils have been either laboratory incubations, column leaching studies, indoor rainfall simulation studies, or other procedures that control confounding variables, and are not representative of real world field and landscape conditions. For example, use of packed rainfall simulation boxes with disturbed soil and infiltration limited by the 5 cm depth and the nine 5-mm-diameter drain holes may not adequately simulate P transport in natural landscapes. The hydrology of bare, packed, sieved soils likely differs from field soils with undisturbed structure, horizonation, and plant coverage. The need for realistic data prompted the validation of some studies with field runoff studies using either natural or simulated rainfall (Gascho et al., 1998; McDowell and Sharpley, 2001). Kleinman et al. (2004) evaluated the use of packed boxes to simulate P transport from agricultural soils and reported practical but limited comparability of the soil box data to field plot data. There is also a need to validate the suitability of the modified (double deck) rainfall simulation box design (described in Chapter 7) to measure P loss in agricultural soils where transport is dominated by leaching and other subsurface mechanisms.

The objectives of this study were to validate the impacts of P-sources and WTR on P loss in a natural field setting and to evaluate the suitability of the modified rainfall simulation box design to measure P loss in soils where leaching is significant.

Materials and Methods

Data from the field experiment described in Chapter 4 were used for this study. The study involved surface application of 4 P-sources at two rates, with or without WTR. In addition to the soil and plant samples collected, ground water and surface water samples were collected. Two wells, one shallow (< 0.9 m) and one deep (~3 m), were installed in the center of each plot 1.2 m apart. The shallow and deep wells were located above, and below, the spodic horizon, respectively (Fig. 9-1). The deep wells yielded samples all year round, including the dry winter periods when the water table falls below the shallow well sampling depth.

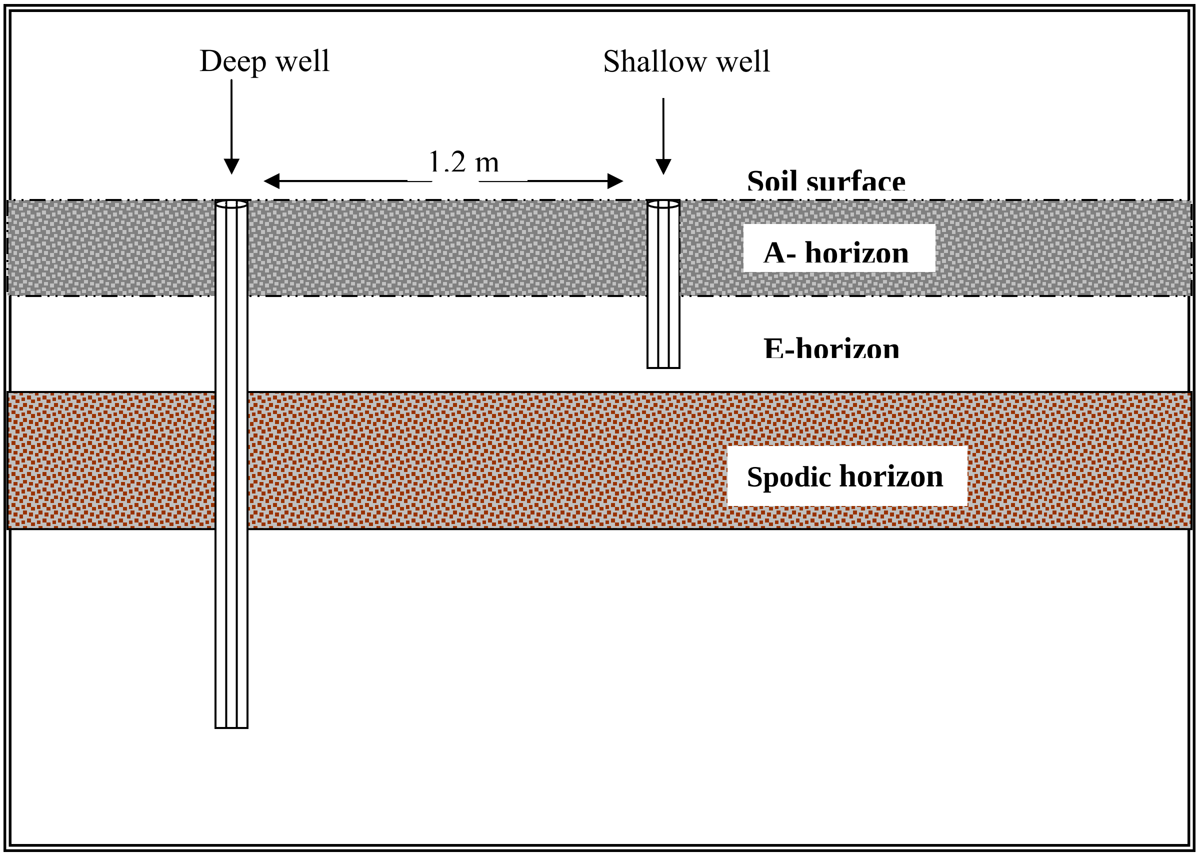


Figure 9-1. Deep and shallow well positions under ground in the field study

The wells were constructed of PVC pipe (5 cm diameter), and were surrounded by a 20 cm diameter casing of the same material. The surface water sampling system included an electronic controller, data logger, and telemetry system to ensure collection of flow-weighted, composite water samples. Each of the experimental plots contained one sampling scheme for surface, shallow, and deep ground waters samples (Fig. 9-2). The wells were located at the center of each plot, while the electronic controller was located at the edge of each plot along the drainage ditch. Figure 9-3 shows the 17 rows of plots (one block or rep) and the surface water sampler with data logger and telemetry system.

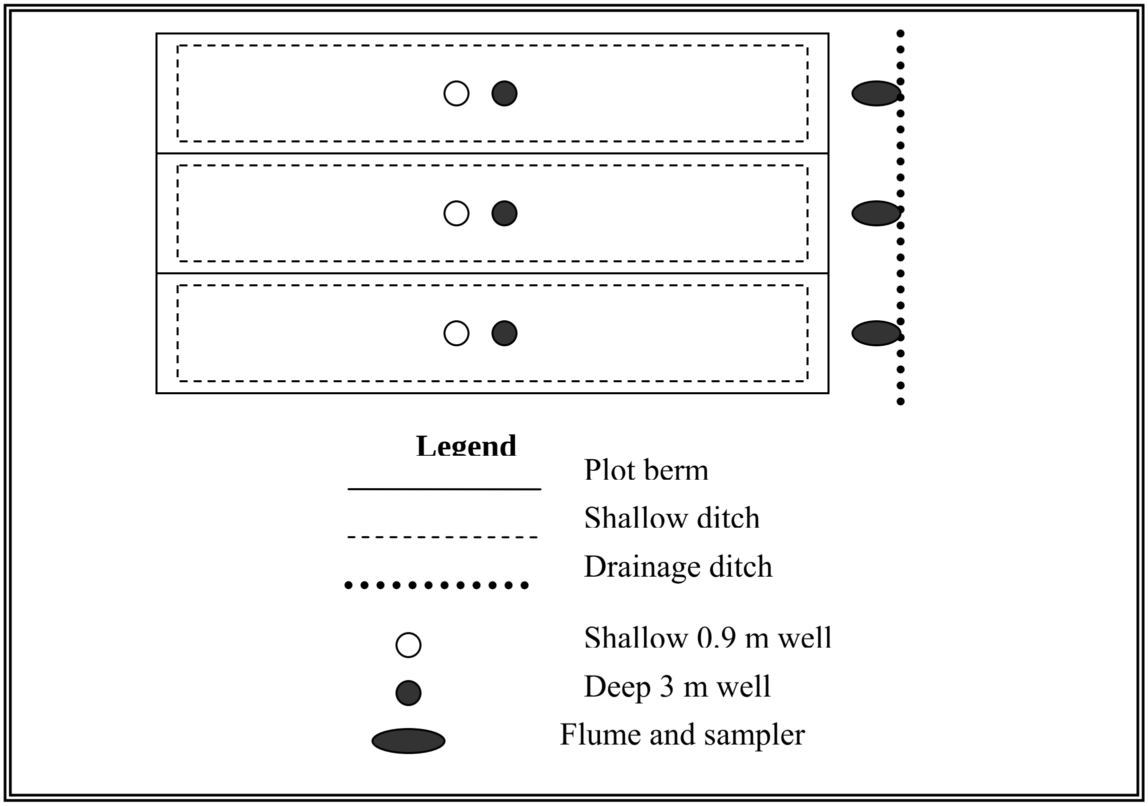


Figure 9-2. Plot layouts and water samplers locations in the field study

Figure 9-3. One of the experimental blocks (replicates) showing the water sampler and the telemetry installed on each of the 17 rows of plots in the field study.

Initial groundwater samples were collected from the deep and shallow wells (but no grab water samples – surface runoff) on March 19, 2003, before treatment application. The Al-WTR (1 % by weight) was applied first, on May 9-13, 2003. The two biosolids and manure were applied from May 13-14, 2003, while the TSP fertilizer was applied on May 19, 2003. Additional water samples were collected from the shallow wells five times in 2003 (June 24, August 19, October 3, November 10 and December 17) and four times in 2004 (August 11 and 30, and September 8 and 30). Deep well samples were collected eight times in 2003 (June 13 and 27, July 17, Aug. 19, Sept. 19, Oct. 20, Nov. 10 and Dec. 22) and seven times in 2004 (March 23, April 28, May 21, June 23, July 13, Aug. 19, Sept. 30). Surface water (grab) samples were collected following periods of high rainfall. Four hurricanes (Charley, Frances, Ivan and Jeanne) impacted Florida within 44 days (August 15 and September 25) in 2004 (Fig. 9-4).

All water samples were analyzed for orthophosphate P (ortho-P), total dissolved P (TDP), and total aluminum concentrations. Orthophosphate P concentrations were determined on the filtered samples colorimetrically with the Murphy and Riley method (1962). Total dissolved phosphorus (TDP) and aluminum concentrations were measured on the filtered water samples after digesting 10 mL of the samples with 0.5 mL 6N H_2SO_4 and 0.15g of potassium persulfate in an autoclave for 1h (Pote and Daniel 2000a and b). Digested samples were analyzed for P colorimetrically (Murphy and Riley, 1962), while ICAP was used to determine Al concentrations. All samplings and analysis were performed in accordance with the Florida Department of Environmental Protection’s standard operating procedures, to minimize sampling and handling contamination (Florida Department of Environmental Protection, 2002a and b).

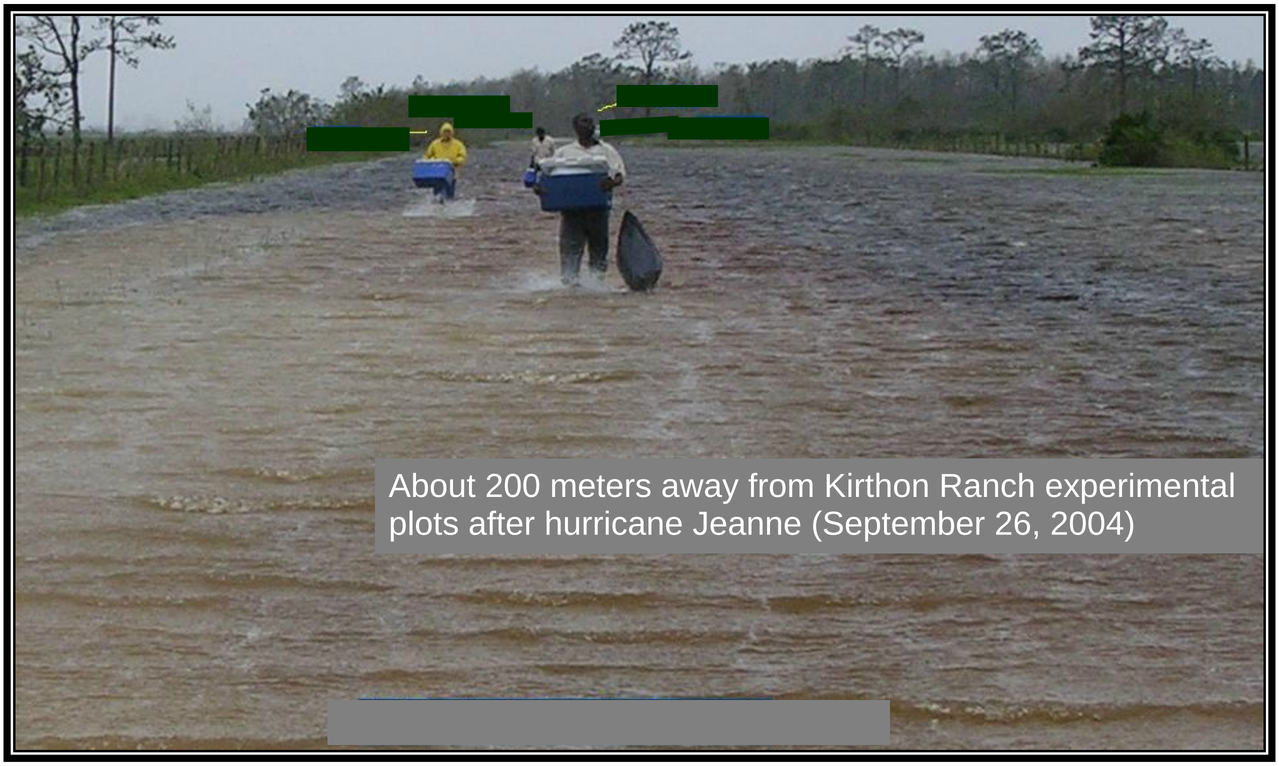


Figure 9-4. Flooding at Kirton Ranch (about 200 meter away from experimental plots) as observed after hurricane Jeanne on September 26th, 2006.

Statistical Analysis

Normality, constant variance and independence tests were carried out on the data and, whenever assumptions of normality and constant variance were violated, appropriate transformation power was determined by Box Cox using SAS (SAS Institute, 1999). Analysis of Variance (ANOVA) was performed on all the data using PROC GLM to determine significant treatment effects (SAS Institute, 1999). When significance was indicated by ANOVA, means multiple comparisons by Tukey test were performed using SAS, at 0.05 significant level. The Cate-Nelson method was used to identify the change point in the relationship between groundwater P and the soil sorption indices.

Results and Discussion

Groundwater Aluminum Concentrations and WTR

The Al concentrations of all the water samples obtained during the study were unaffected by WTR rate, P-source, or P-source application rates. The ranges of Al concentrations in samples obtained after treatment application were 0.4 to 1.2 mg L^{-1}, and 0.7 to 2.7 mg L^{-1} for the shallow and deep wells, respectively. The ranges compared well with the concentration ranges in samples obtained before treatments application (0.6 to 2.4 mg L^{-1} for shallow wells and 1.0 to 3.8 mg L^{-1} for deep wells) on March 19, 2003. The trends of Al concentrations in samples obtained before and after treatment applications (2003-2004) are shown in Fig. 9-5.

Generally, the Al concentrations were greater in the deep wells than in the shallow wells, which could result from contributions of organic Al species to Al solubility in the spodic horizon and not from the surface-applied treatments. Nilsson and Bergkvist (1983) studied Al chemistry in a Swedish podzols, and reported greater total Al concentrations (95 to 115 μM L^{-1} or 2.6 to 3.1 mg L^{-1}) in leachate samples below the Bh-horizon, than below the A-horizon (3.3 to 47 μM L^{-1} or 0.09 to 1.3 mg L^{-1}). Thus, surface-applied Al-WTR increased soil total Al concentrations of surface soils, but did not affect Al concentrations in shallow or deep ground waters or runoff (grab) samples (Fig. 9-6). The ground water Al data were consistent with the results obtained from studying agronomic impacts of applied WTR in the field and the glasshouse, where plant Al concentrations were the same in WTR-amended and unamended soils. Thus, WTR can be safely used to enhance the P-sorption capacity of Florida soils and reduce soluble P losses without increasing soluble Al concentrations in water or Al concentrations in plants.

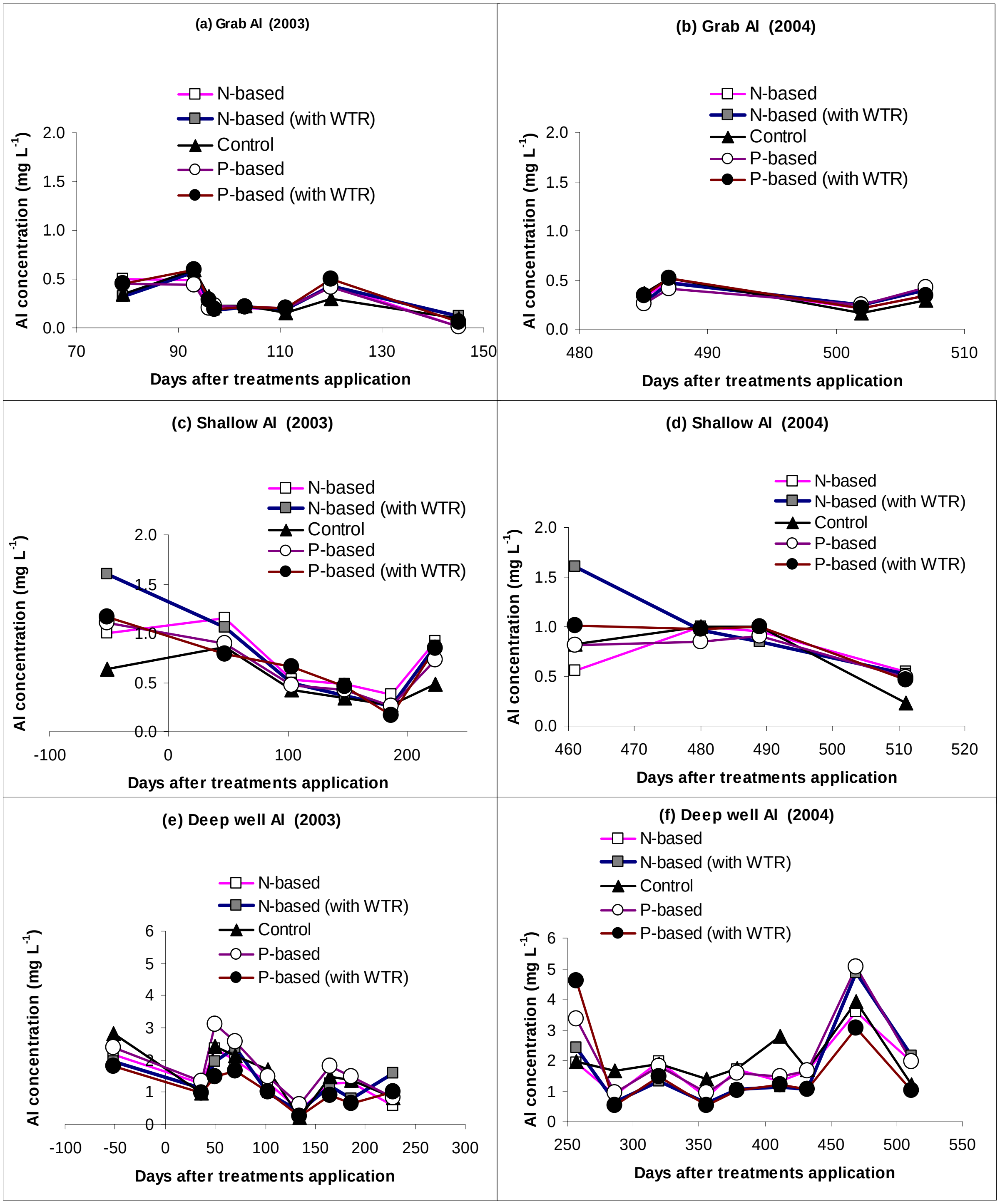


Figure 9-5. Trends of Al concentrations surface grab (a and b), shallow well (c and d) and deep well (e and f) water samples taken during the study.

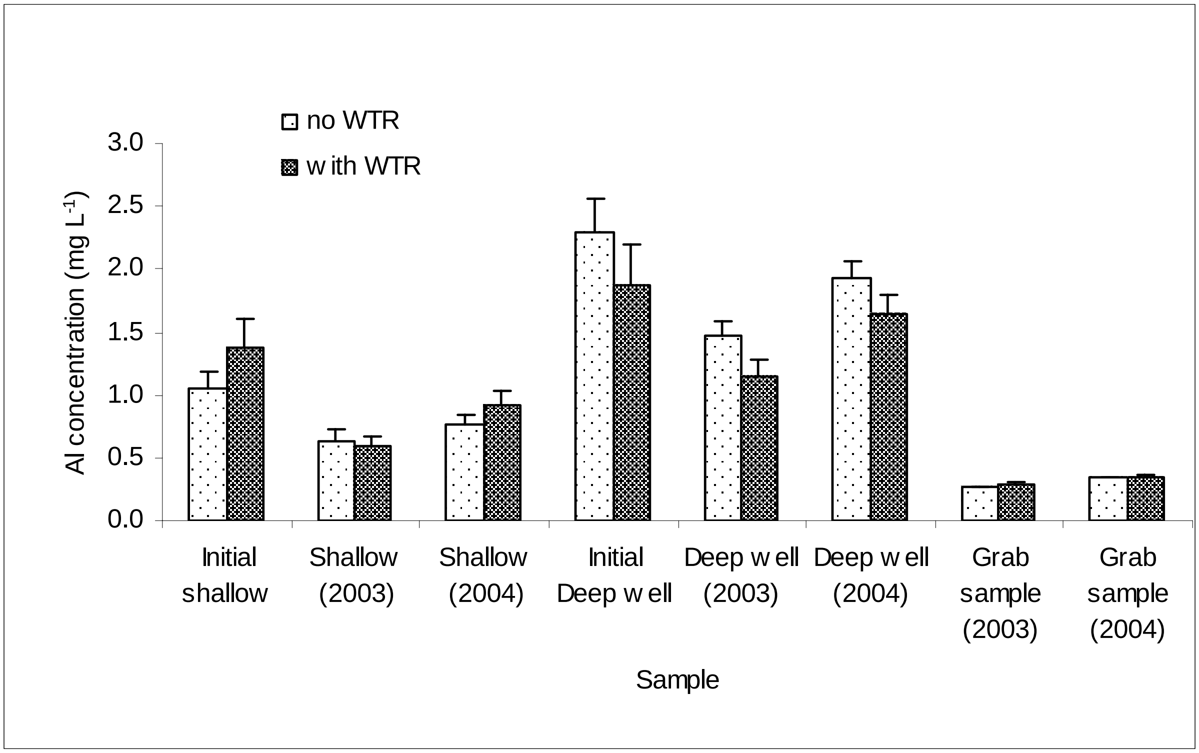


Figure 9-6. Aluminum concentrations in water samples taken during the study as affected by surface applied WTR (n = 24, error bars represent one standard error).

Groundwater P Concentrations and WTR

The groundwater P concentrations indicated greater ortho-P than total dissolved P (TDP) in some cases, an anomaly that is still being investigated (South Florida Water Management District, 2003). However, the analysis was done in a certified laboratory (Analytical Research Laboratory, UF (ARL)) with precision and accuracy ensured (5% duplicate and QC check samples and recoveries of 95 - 110%). Reagent and method blanks analyzed also indicated no contamination. Other quality control measures included matrix spikes and continuing calibration standards. Some samples were send to other certified laboratories (UF-IFAS Southwest Florida Research Laboratory (SWFRL); Wetland Biogeochemistry Laboratory, UF; and Lee County

Laboratory) for ortho-P duplicate analysis. Total P could not be reanalyzed by the other laboratories because the laboratories are not sufficiently equipped for the analysis.

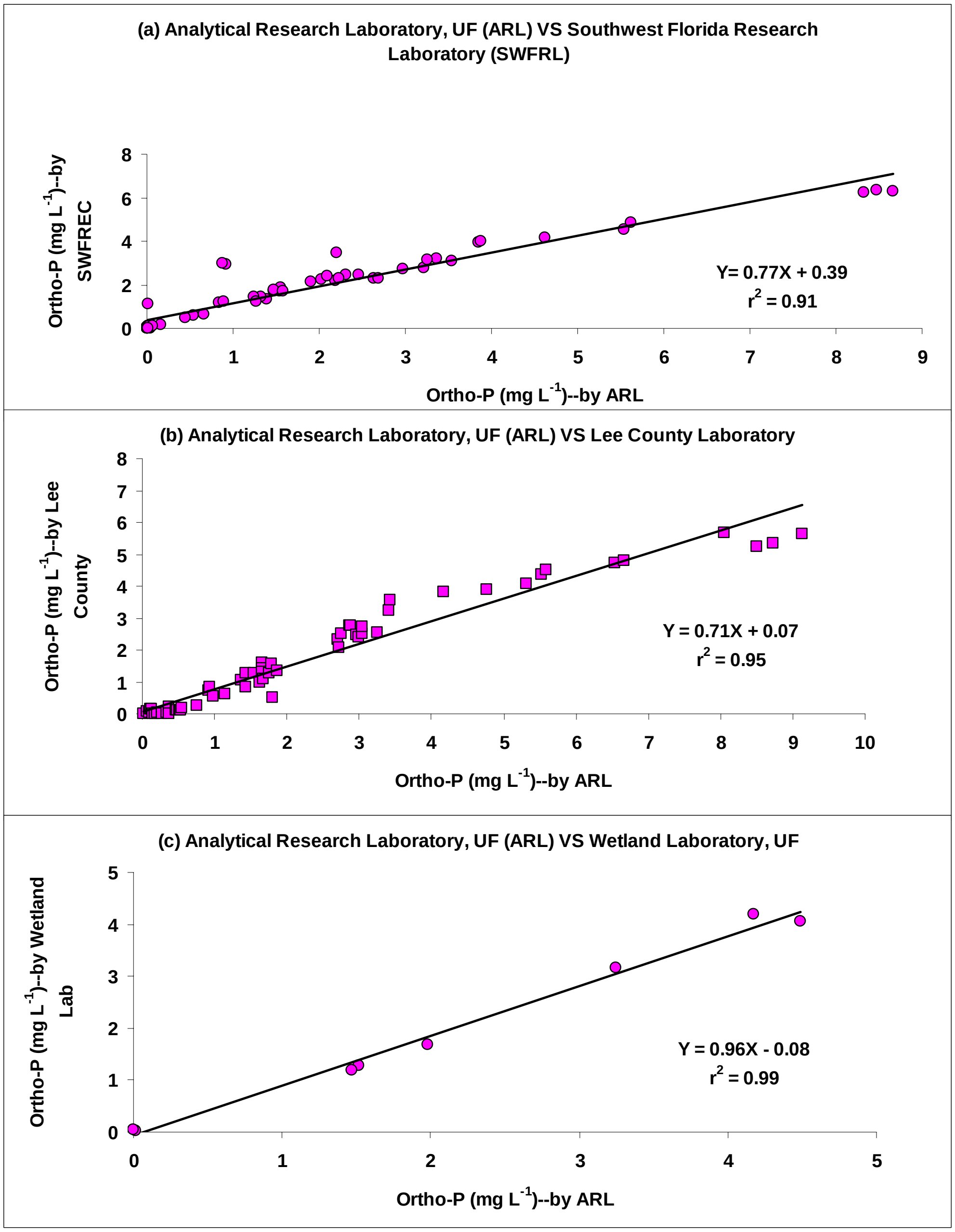


Figure 9-7. Regression of ortho-P concentrations results in groundwater samples reanalyzed by three other laboratories (UF-IFAS Southwest Florida Research Laboratory (SWFRL); Wetland Biogeochemistry Laboratory, UF; and Lee County Laboratory) with values obtained from Analytical Research Laboratory.

Comparison of duplicate results indicates consistently greater ortho-P concentration values of samples analysed by ARL than other laboratories (Fig. 9-7). However, the results from ARL have similar trend as in other laboratories ($r^2 > 0.9$), which suggests the error may be systematic. Thus, inferences about the absolute values of the P concentrations may be limited, but trends of the treatment effects could still be studied.

Analysis of variance indicated that P concentrations of water samples taken from deep and shallow wells were affected by the surface-applied WTR, but not by P-source or P-source application rate throughout the study (2003-2004). There were no effects of P-source, P application rate, or WTR addition on P concentrations in the surface water grab samples collected during the two-year experiment.

Trends of the water P concentrations for each P-source rate treatment (with and without WTR) for all sampling periods in 2003 and 2004 are shown on Fig. 9-8. The grab samples had similar P concentrations in samples obtained from plots treated at N-based and P-based rates, and whether WTR was applied or not. The observed similar grab water P concentrations of samples from WTR treated and untreated plots are inconsistent with effectiveness of WTR at reducing runoff P concentrations observed during rainfall simulation study. The inconsistency could not be explained, but may result from the differences in material (P-sources and WTR) application in the two studies. The P-sources were applied first followed by WTR (on top) during the rainfall simulation study, but the other way round (WTR first then the P-source) in the field.

Though the effect of WTR was not observed in the grab samples, the added WTR reduced P concentrations in groundwater samples throughout the study. Both ortho-P and TDP concentrations were greater in the absence, than in the presence, of WTR at both P-source rates (Fig. 9-8 and 9-9). Surface applying WTR at 1% reduced groundwater P concentrations at both

P-based and N-based source rates below P concentrations observed in control treatment. Shallow well P concentrations for both P-source rates were similar in the presence of WTR in almost all the samples taken during the study. Thus, the added WTR masked the effect of P-source rates on ground water P concentrations.

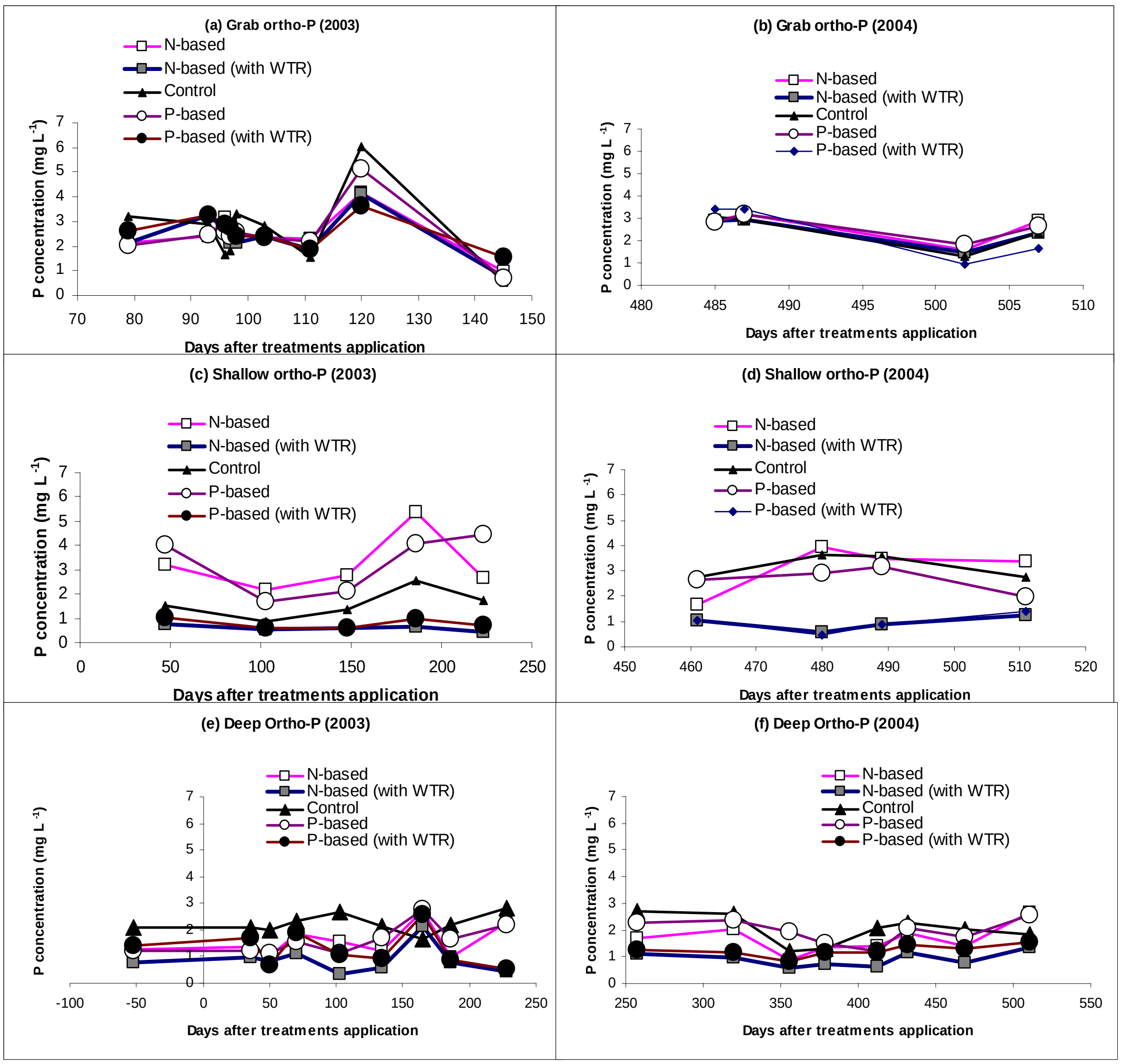


Figure 9-8. Trends of ortho-P concentrations for the various treatments in surface grab (a and b), shallow well (c and d) and deep well (e and f) water samples taken during the study. (Note: Data for “pre-application” shallow well samples are pending in the lab as of the time of this report, and no surface grab samples were taken until 130 days after treatment application).

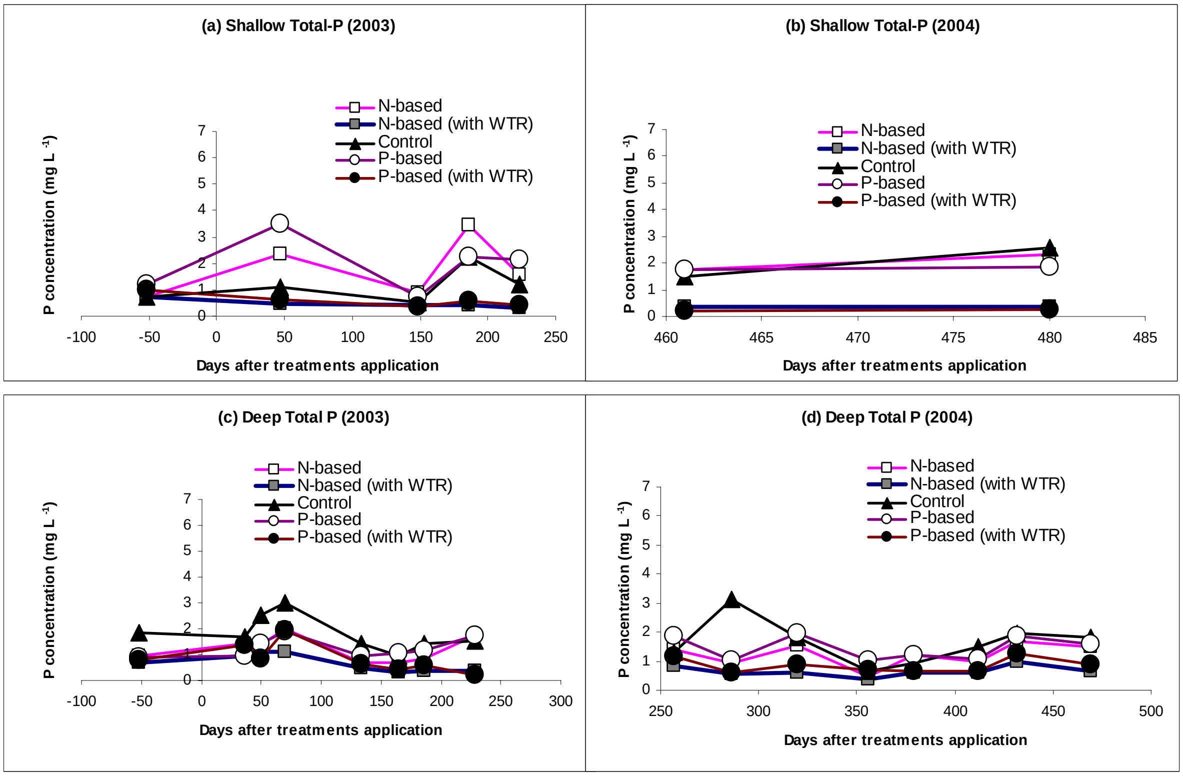


Figure 9-9. Trends of total dissolved P concentrations for the various treatments in shallow (a and b), and deep well (c and d) water samples taken during the study

The impact of WTR on P concentrations of samples from deep wells was not as pronounced as in shallow wells (Fig 9-9). The WTR effects were likely confounded by the Al-rich spodic horizon above the sampling point of deep wells. The spodic horizon sorbs P, as does WTR. Samples taken before treatment application have similar P concentrations, and the grab samples were not affected by the WTR (Fig 9-10). However, all ground water samples taken from deep and shallow wells contained greater P concentrations in the absence, than in the presence, of WTR throughout the study. The effectiveness of WTR at reducing soluble P was reflected in the water P concentrations, even in 2004 samples, with greater hurricane activity.

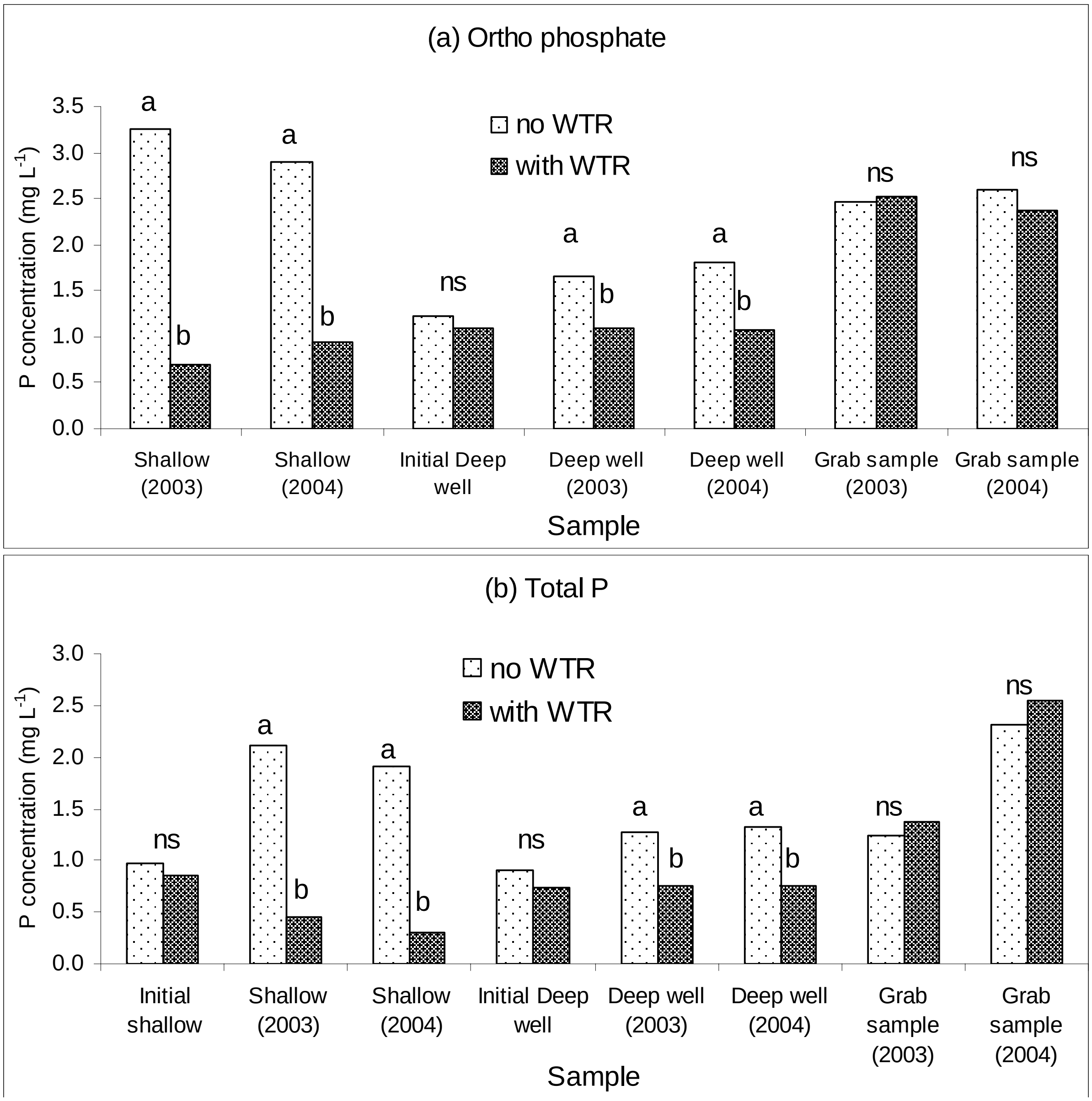


Figure 9-10. Total dissolved and Ortho-P concentrations of water samples taken during the study as affected by WTR application. Treatments bar within the same sampling period capped by the same letters are not different at p = 0.05 by Tukey test

Soil P Sorption Indices and Groundwater P Concentrations

Studies on acidic sandy soils have shown good correlations between soil soluble P and the degree of P saturation (DPS) values, which are calculated from oxalate extractable P, Fe, and Al of soils (Beek, 1979; Nair and Graetz, 2002). Another index of soil P sorption is the soil P storage capacity (SPSC), which is also calculated from the extractable P, Fe, and Al as explained in previous chapters (Chapter 3, 4, and 6). Data from both glasshouse and field studies showed that soil sorption of P increased with WTR application, and that WTR effects were correlated with changes in DPS and SPSC values.

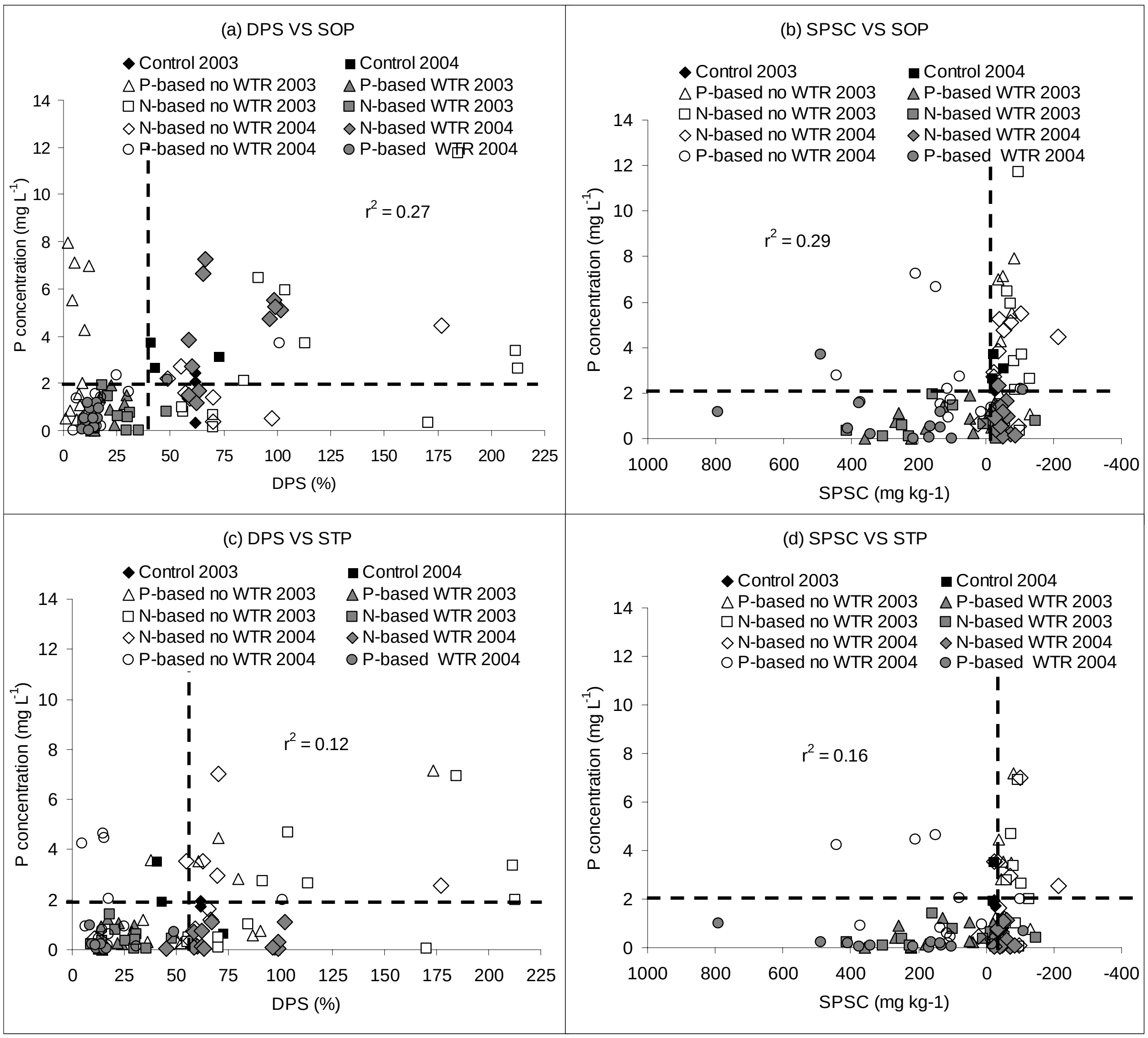


Figure 9-11. Relationships between soil P sorption indices (Degree of P saturation (DPS), and soil P storage capacity (SPSC)) and shallow well water ortho-P (SOP), and Total dissolved P (STP) concentrations.

Soil DPS values were reduced below the environmental threshold, with accompanied reduction in soil soluble P, when WTR was applied. Also, SPSC values were increased in all P-sources treatments, and at both P-source application rates following addition of WTR. The reduction in soil soluble P concentrations with increasing soil P sorption properties noted earlier (Fig. 4-6) was confirmed by this study (Fig. 9-12). Generally, the relationships between the groundwater P concentrations and the soil sorption indicies (DPS and SPSC) were very poor ($r^2 < 0.3$). However, change points were easier located by the Cate Nelson procedure at ~0 mg kg^{-1} SPSC, than at 25% DPS thresholds. Thus, the data support the contention of Nair and Harris (2004) that SPSC value is a better indicator of environmental P hazard than DPS. The SPSC values better assesses the capacity of a soil to retain P and, thereby, reduce groundwater P concentrations.

Summary and Conclusions

The greater soil total Al concentrations of surface soils following surface application of Al-WTR did not increase Al concentrations in surface water, or shallow and deep groundwaters. The data support the contention that WTR can be safely used to enhance P sorption capacity of Florida sandy soils without increasing groundwater Al concentration.

Surface-applied WTR reduced groundwater P concentrations in all the P-source and P-source rate treatments to values below those observed in the control treatment. The impact of WTR on P concentrations of deep well samples was pronounced despite the confounding effect of the Al-rich spodic horizon above the sampling point.

The P concentrations of water from the shallow wells related better with SPSC values than DPS values, supporting the use of SPSC values as measures of soil capacity to retain P and protect against environmental P hazard.

CHAPTER 10
SENSITIVITY ANALYSIS OF THE DRAFT FLORIDA P INDEX

Introduction

Phosphorus source, P-source rate, and sorption properties of the soils are among variables shown by this study to affect P losses in Florida sands. Thus, appropriate management to reduce P losses requires estimates of P loss potential from landscapes using a model that is sensitive to the variables. The phosphorus index (P Index) is a site-specific, qualitative vulnerability assessment model being developed by states (including Florida) for P management plans to reduce P losses and address water quality (USEPA, 1999). The Florida P Index will help to determine whether organic sources of P should be applied at N-based or P-based rates and other suitable site specific nutrient management systems that could be employed. However, there is need to study the sensitivity of the Florida P Index model to the variables identified to affect P losses.

Basically, the concept of the P Index is that management of agricultural P should target the critical point at which P-source and transport factors overlap (Gburek and Sharpley, 1998). Thus, the P Index developed by all the states in the US identifies “source” and “transport” variables that could account for P losses. The original P Index by Lemunyon and Gilbert, (1993) contained five source and three transport variables, each assigned five discrete ratings. The draft Florida P Index differs slightly, and contains four variables related to site and transport (Table 10-1, Part A) and five source variables (Table 10-1, Part B). The transport variables (i.e. soil erosion, runoff potential, leaching potential, and potential to reach water body) are assigned discrete ratings to describe the magnitude of each variable. Application method and P-source applied are also assigned discrete ratings, but other source variables (fertility index value, P application rate, and waste water application) have continuous ratings.

Table 10-1. The draft Florida P Index worksheet

Part A: Transport potential due to site and transport characteristics						
Site and Transport characteristics	Phosphorus transport rating					Value
Soil Erosion	No surface outlet 0	< 5 T/A [a] 1	5-10 T/A 2	10-15 T/A 4	> 15 T/A 8	
Runoff Potential	Very Low 0	Low 1	Medium 2	High 4	Very High 8	
Leaching Potential	Very Low 0	Low 1	Medium 2	High 4	Very High 8	
Potential to reach water body	Very Low 0	Low 1	Medium 2	High 4		
Total for part A: Site and Transport [b]						

[a] T/A = tons per acre.
[b] if the sum of part A is 0 (zero), then change the sum to 1 (one).

Part B: Transport potential due to phosphorus source management					
Phosphorus source Management	Phosphorus Loss Rating				Value
Fertility Index Value	Soil Fertility Index X 0.025 (___ppm P X 2 X 0.025) [c]				
P Application Source and Rate[d]	0.05 X (__lbs P_2O_5/acre) for fertilizer, manure, or compost 0.015 X (___lbs P_2O_5/acre) for biosolids 0.1 X (___lbs P_2O_5/acre) for waste water				
Application Method	No Surface Outlet or solids incorporated immediately or injected 0	Applies via Irrigation or solids incorporated within 1 day of application 2	Solids incorporated within 5 days of application [e] 4	Solids not incorporated within 5 days of application 6	
Waste Water Application	0.20 X _acre inches/acre/year				
Sum for Table 2: Phosphorus Source					

[c] From soil test (Mehlich 1) results.
[d] Initial evaluation should be N-based rates
[e] Solids include fertilizers, composts, biosolids, and manure and other animal wastes
P Index score = Σ (site and transport ratings)* Σ (Phosphorus source rating)

The P Index score (i.e. overall P loss vulnerability rating) is obtained by multiplying transport and source total values as:

$$I = (R_{SE} + R_{RP} + R_{LP} + R_{PWB})*(R_{FIV} + R_{AM} + R_{WWA} + R_{PAS}*R_{PSAR}) \qquad \textit{Equation 10-1}$$

Where I = *P Index score;* R_{SE}, R_{RP}, R_{LP}, R_{PWB}, R_{FIV}, R_{AM}, R_{WWA}, R_{PAS}, R_{PSAR} are site ratings for soil erosion, runoff potential, leaching potential, potential to reach water body, fertility inde value, application method, waste water application, P-source applied, and P application rate, respectively.

The Florida P Index is a linear model, as the relationship between the P Index score and the variables is first order. Prior to implementing the Florida P Index, the model should be tested, and the impact of each variable on P loss evaluated in the field. However, the first step should be a sensitivity analysis to evaluate the variables included in the P Index and to ensure the conformity of the P Index model to the intentions of the developers (Brandt and Elliott, 2005). Sensitivity analysis is a tool that can help the modeler and the users understand the importance of variable inputs on the computed outputs. The sensitivity analysis can be classified based on the model type (as mathematical, statistical, and graphical) or based on capability, rather than the methodology, of a specific technique. For example, deterministic analysis, using mathematical method such as nominal range sensitivity, can be employed to evaluate model variables sensitivity. Alternatively, an analyst may perform a probabilistic analysis, using either frequentist or Bayesian frameworks, in which case statistical-based sensitivity analysis methods can be used.

The nominal range sensitivity analysis (NRSA) employed in this study is a mathematical method that assesses the sensitivity of model output to the range of variation of each input variable. The NRSA involves calculating and studying the change in the output within possible ranges of the input values. Graphical methods, which visually represent sensitivity in the form of graphs, charts, or surfaces, are compatible with NRSA and can be used to complement the results. The NRSA addresses only a potentially small portion of the possible space of input values, as interactions among inputs are not captured (Cullen and Frey, 1999). Thus, the NRSA will determine the degree to which P Index score changes per unit change in the impact variables. The sensitivity of each input variable is determined by the slope (i.e. changes in output score with unit change in input values) obtained from the plot of P Index scores with increasing values of each variable. If a small change in a variable value results in a relatively large change in the P Index score, the P Index is said to be sensitive to that variable. The NRSA is an important method for assessing the quality of a model, model robustness, and reliability of the model analysis. The sensitivity analysis can also help direct future studies. Variables to which the model is relatively sensitive could require further characterization, while possible causes of insensitivity to other variables may need to be investigated. The objective of the study is to utilize sensitivity analysis to evaluate the suitability of draft Florida P Index model as a tool for P management in different landscapes.

Materials and Methods

The nominal range sensitivity analysis procedure used by Brandt and Elliott (2005) was adapted for this study. Nominal range sensitivity analysis can evaluate the effect exerted on model outputs by individually varying only one of the model inputs across the entire range of plausible values, while holding all other inputs at nominal or baseline values (Cullen and Frey, 1999). The difference in the model output due to the change in the input variable is referred to as the “sensitivity” or “swing weight” of the model to that particular input variable (Morgan and Henrion, 1990). The sensitivity analysis can be repeated for any number of individual model inputs and is most valid when applied to a linear model such as the draft Florida P Index.

The Florida P Index is a linear model, as it can be represented by first order linear equation as:

$$I = (R_{SE} + R_{RP} + R_{LP} + R_{PWB})*(R_{FIV} + R_{AM} + R_{WWA} + R_{PAS*}R_{PSAR})$$

Where $I = P\ Index\ score$

The sensitivity of the P Index score (S_i) with respect to variable "*i*", when all other input variables are kept constant at baseline (X_i) can be computed as:

$$S_i = \frac{\delta I}{\delta X_i} = \frac{\Delta I}{\Delta X} \qquad \textit{Equation 10-2}$$

X_i = condition where input variables are at baseline except variable *i*

The variables in the P Index model are a mixture of continuous and discrete variables, which differ from each other in units. To enhance variable comparisons using similar units, dimensionless sensitivity coefficients (S_i') were computed by expressing each variable as percentage of the respective baseline value.

$$S_i' = \frac{I(X_i + \Delta X_i) - I(X_i)}{100*[((X_i + \Delta X_i)/(X_i)]} \qquad \textit{Equation 10-3}$$

where $I(X_i)$ and $I(X_i + \Delta X_i)$ are P Index scores for baseline and perturbed values, respectively (Brandt and Elliott, 2005). The sensitivity of the variables in the P Index are compared using the slope (S_i) obtained for each variable (Eschenbach, 1992). The greater the slope obtained for a variable, the more sensitive the P Index score to the variable.

The relative importance of each input can be rank-ordered based upon the magnitude of calculated sensitivity measures, provided the ranges assigned to each sensitive input are accurate. Thus, the study requires realistic domain limits (ranges) and baseline conditions for each variable input. Below is a summary of the basis and justification of parameter selections for each of the nine input variables.

Phosphorus Application Source (PAS): To account for P-sources, the P Index contains three PAS values (0.05 for fertilizer, manure or composts, 0.015 for biosolids and 0.1 for waste water). Thus, the range of PAS values in the P Index, 0.015 – 0.1, is used as the domain limits, while the median value (0.05) represents the PAS baseline condition.

Phosphorus Source Application Rate (PSAR): The PSAR values are selected based on UF/IFAS standardized fertilization recommendation for agronomic crops (Kidder et al., 2002). The minimum value was taken to be zero, representing a condition in which no P is applied. The maximum UF/IFAS recommended P-source rates are 175 lbs P_2O_5 $acre^{-1}$ yr^{-1} (P-based) and 210 lbs PAN $acre^{-1}$ (N-based). Typically, ~224 kg P ha^{-1} (450 lbs P_2O_5 $acre^{-1}$) is assumed to represent P load at N-based rates of organic amendments (Stehouwer et al., 2000). Hence, 450 lbs P_2O_5 $acre^{-1}$ was chosen as the upper limit of the domain. The 225 lbs P_2O_5 $acre^{-1}$ is half of the 450 value used as representating P loads at N-based rates and was chosen to represent the baseline value.

Application Method (AM): The draft P Index rates P application method from zero (when the solids are incorporated immediately or injected) to 6 (when the solids are not incorporated within 5 days of application). Thus, the range 0-6 is used as the domain limit. In Florida, the common management practice is surface application without incorporation when the amendment are applied to established pasture (rating = 6), or incorporated within 1-5 day when applied to other agronomic crops (rating 2). Thus, the median value of the two ratings assigned to these practices is "4" and is used as the baseline value for AM.

Fertilizer Index Value (FIV): The FIV is calculated from the soil test P (STP) as:

$$FIV = STP*2*0.025$$

The variable is the STP, and as a continuous variable, could range from zero to maximum values determined from the field where the P Index is applied. An upper limit of 300 ppm was used here based on a field survey study of potential sites for P Index use (personal discussion with Dr. V.D. Nair). Thus, the range 0-300 ppm STP, which is equivalent to FIV values of 0 – 15, was used as the domain. The M-1P STP interpretation used for agronomic crops are: very low (< 10 ppm), low (10 – 15 ppm), medium (16 – 30 ppm), high (31 – 60 ppm) and very high (> 60 ppm). Based on the median of high STP, a value of 40 ppm was used as baseline STP (equivalent to FIV value of 2).

Waste Water Application (WWA): Sewage waste water or effluent is land applied in Florida to meet irrigation needs. In studies on land application of waste water in Florida, the application rate ranges from 400 mm (25 acre inches yr^{-1}) to 1250 mm (~ 50 acre inches yr^{-1}) (Maurer et al., 1995; Parsons et al., 2001). The P concentration ranges from 0.01 mg L^{-1} to 10 mg L^{-1}, with average of 3.88 mg L^{-1}. Thus, the range of WWA values used for the study was 0 acre inches yr^{-1} (when no water is applied) to 50 acre inches yr^{-1}. The commonly used rate in Florida, (400 mm, equivalent to 25 acre inches yr^{-1}; Parsons et al., 2001) was used as the baseline value. The P rate (P load) at the 50 acre inches yr^{-1} and at maximum concentration (10 mg L^{-1}) falls within the range of PSAR used (0 - 450 lbs P_2O_5 $acre^{-1}$).

Phosphorus Transport Potential due to Site and Transport Characteristics: The transport component of the P Index consists of four variables: Soil erosion (SE), runoff potential (RP), leaching potential (LP), and potential to reach water body (PWB). The four variables are each assigned discreet categorical ratings that serve as the domain limits (range) in this study. Thus, the domain limits are 0 to 8 (for SE, RP, and LP), and 0 to 4 (for PWB), and are the ranges of the ratings assigned to the variables.

Data of runoff and leaching potential ratings for Florida soil survey map units (summarized by Hurt et al., 2006), were used to select baseline values representative of Florida soils. The number of map units associated with undrained runoff, drained runoff, and leaching potential (categorized into very low, low, medium, high, and very high), in Florida soils for all counties pooled together is shown in Fig. 10-1a. Since drained and undrained runoff is not distinguished in the P Index, the two variables are pooled to obtain the values for runoff potential (Fig. 10-1b).

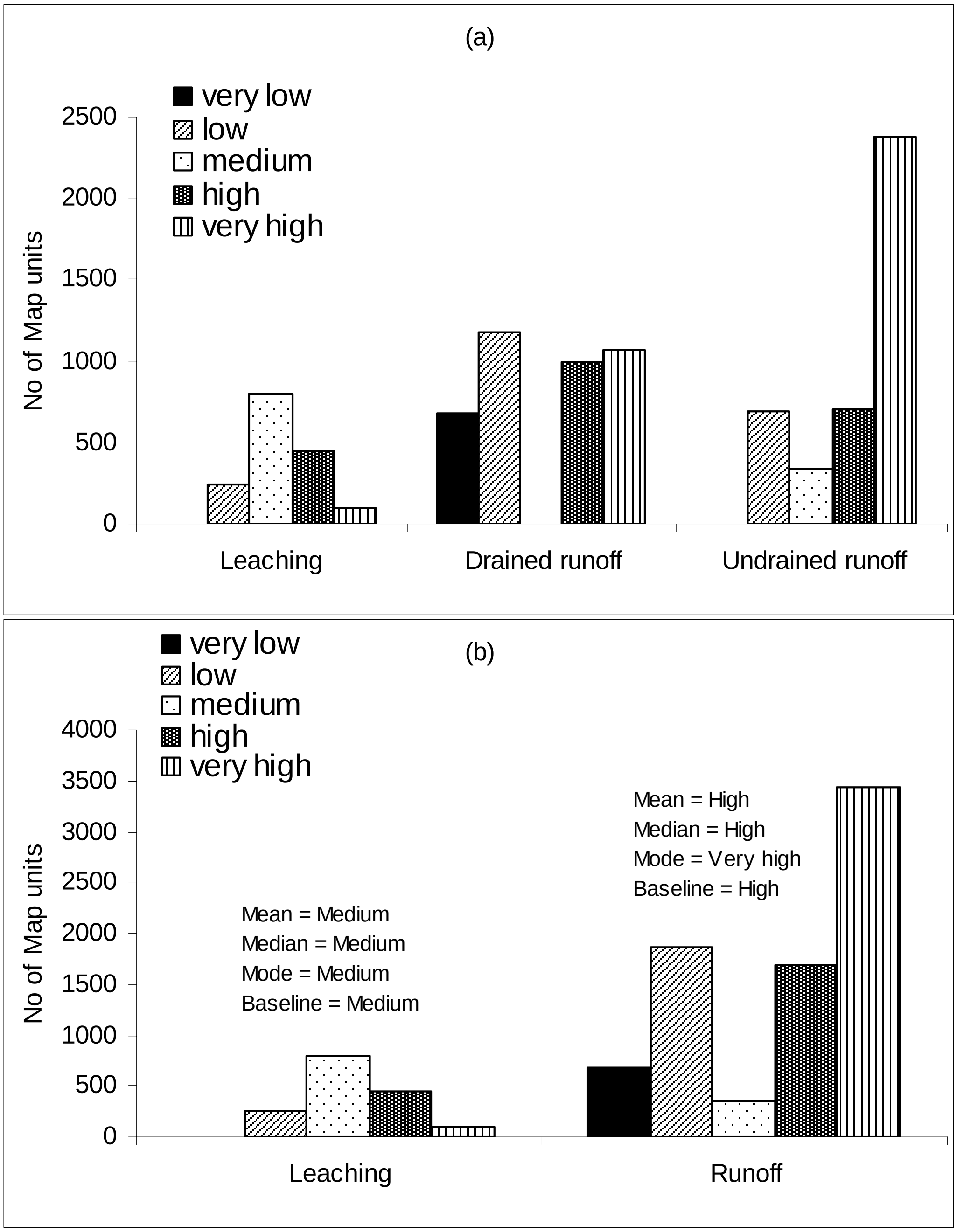


Figure 10-1. Number of map units associated with (a) undrained runoff, drained runoff and leaching potential and (b) reclassified to runoff and leaching potential rated very low, low, medium, high, and very high in Florida soils.

The baseline values are selected for each transport variable (Table 10-1), based on the distribution of runoff and leaching potential categories for all counties in Florida. The summary statistics of the map units indicates the “medium” category (rating = 2) as the mean, median, and mode of the leaching potential. Also, the mean and median of runoff potential is “high” (rating = 4), but its mode is “very high” (rating = 6). Based on the summary statistics, the baseline values used are medium (rating = 2) for leaching potential and high (rating = 4) for runoff potential.

From the description of the PWB rating criteria, the “low” category (rating = 1) describes the situation in which P in runoff can be attenuated by flow through a wetland, buffer strip or overland treatment area. A “low” rating (value = 1) describes common situations in agricultural areas and was selected as the baseline value for PWB. The SE factor was indicated to be <5T/A in most counties in FL by Hurt et al. (2006), and identified baseline value for SE as “1”. Table 10-2 summarizes the input values (domain limits and the baseline) for each of the nine variables used in the NRSA.

Table 10-2. Input values for each variable used in nominal range sensitivity analysis of draft Florida P Index

Variable	Unit	Domain limits		Baseline condition
		Minimum	Maximum	
Fertility index value	-	0	15	2
P-source	-	0.015	0.1	0.05
P-source rate	lbs P_2O_5	0	450	225
Application method	-	0	6	4
Waste water	-	0	4	2
Soil erosion	-	0	8	1
Runoff potential	-	0	8	4
Leaching potential	-	0	8	2
Potential to reach water body	-	0	4	1

Results and Discussion

Sensitivity of the Draft Florida P Index Model to the Variables

The sensitivity of the P Index variables is compared using the slope obtained for each variable in the spider plot (Fig 10-2). The score for base condition (178) fell within the high P-index rating, which dictates P-based management. The high baseline score suggests that most Florida landscapes will be rated high by the draft P-index. The steeper the slope of a variable in the spider plot (sensitivity coefficient), the more sensitive the P Index score to the variable.

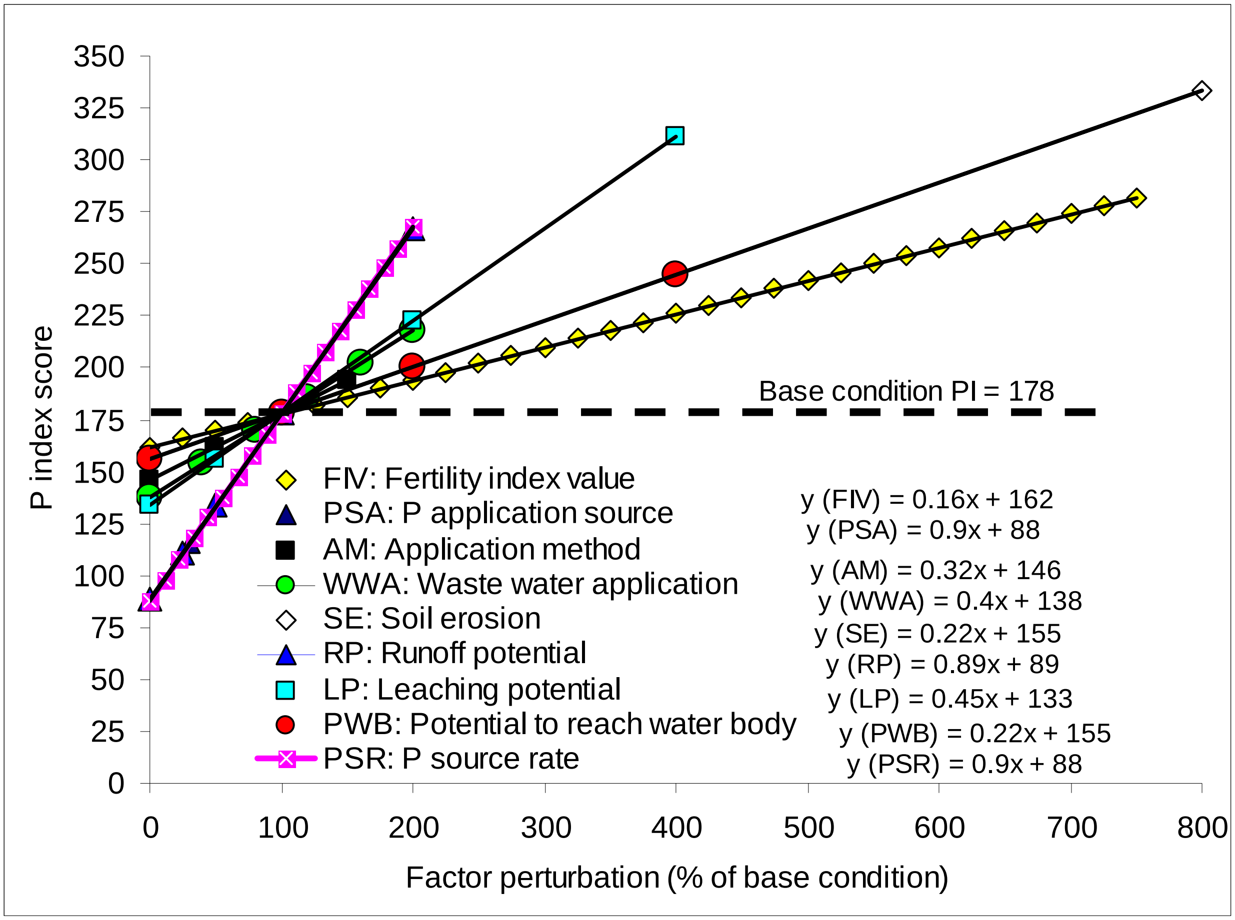


Figure 10-2. Spider diagram of variables in the draft Florida P Index.

Figure 10-2 indicates that both PAS and PSAR have the greatest sensitivity coefficients (0.90) and, hence, exert the greatest impact on the P Index score. A 100% increase in the PSA or PSAR baseline ratings increase the P Index score by 90 points. The lowest sensitivity coefficient (0.16) was observed for the FIV regression. Increasing the soil test P from 40 ppm to 80 ppm only increases the P Index score by 16. Thus, the draft Florida P Index is not especially sensitive to the STP comparared to other variables. Reducing STP from 40 ppm to 0 ppm only reduces the P Index score by 16. As the impact appears counterintuitive, the result may need to be verified by experimental data. The nine variables are categorized into six sensitivity coefficient groups: 0.90 (PSA and PSAR), 0.89 (RP), 0.45 (LP), 0.40 (WWA), 0.32 (AM), 0.22 (SE and PWB), and 0.16 (FIV). Some questions posed by the sensitivity analysis results are obvious and should be addressed before validation with experimental data. For example, the sensitivity coefficient of AM was greater than that of FIV. The AM may be more important than FIV in soils where subsurface runoff flow is not an issue. However in Florida sandy low P-sorbing surface soils with extensive subsurface flow, AM may not affect P loss as much as FIV. An important application of the sensitivity coefficients is aiding nutrient managers in identifying the impacts of varying management practices. For example, a management practice to attain zero SE (and every other variable at baseline) will only reduce the P Index score by 22. However, if instead of managing SE, the AM is improved by ensuring amendments or P-sources are immediately incorporated (rating = 0) instead of waiting 2 days or more to incorporate the solids (rating = 4), the P Index score is reduced by 32. Thus, P-source incorporation can change the field rating from a P Index score of 178 (P-based management) to 146, which allows N-based management. However, the question still remains. Does incorporation make so much difference in Florida soils with regards to P loss? Result from rainfall simulation study (Chapter 7) indicated greater P loss through leaching though the P-sources were surface applied (and not incoporated). Thus, application method may have little impact in Florida soils where greater P losses are through leachate. However, field data are needed to test the impact of placement method on P loss.

An important observation from the spider plot is that both the coefficients (slope) and the length of the regression lines (range of P Index score covered by each variable) vary. Thus, a variable may have a greater coefficient, but cover a smaller P Index score range. A good example is PSA, which has a larger sensitivity coefficient, but a smaller range than either LP or SE. The range of P Index scores covered by each variable is called the swing, and calculated as:

$$Swing = I(X_i^{max}) - I(X_i^{min}) \qquad \textit{Equation 10-4}$$

Where $I(X_i^{max})$ and $I(X_i^{min})$ are the P Index scores at maximum and minimum values, respectively, of the i^{th} variables (keeping all other variables at baseline).

The calculated swings (also called tornado swing), and sensitivity coefficients for each variable are shown on Table 10-3.

Table 10-3. Sensitivity coefficients and swings and normalized values for each variable in the draft Florida P Index

Input factor	Spider Sensitivity Coefficient	Tornado Swing	Normalized Sensitivity Coefficient (%)	Normalized Swing (%)
Fertility index value	0.16	120	18	67
P-source	0.90	153	100	85
P-source rate	0.90	180	100	100
Application method	0.32	48	36	27
Waste water	0.40	80	44	44
Soil erosion	0.22	178	24	99
Runoff potential	0.89	178	99	99
Leaching potential	0.45	178	49	99
Potential to reach water body	0.22	89	24	49

The table also contains the normalized sensitivity coefficients and normalized tornado swings that express each sensitivity coefficient and swing value as a percentage of the observed greatest values of the sensitivity coefficients and the swings, respectively. The swing is represented graphically as tornado swing in Fig. 10-3. The tornado swing indicates the range of impact each variable has on the P Index score if all other variables are left at baseline value.

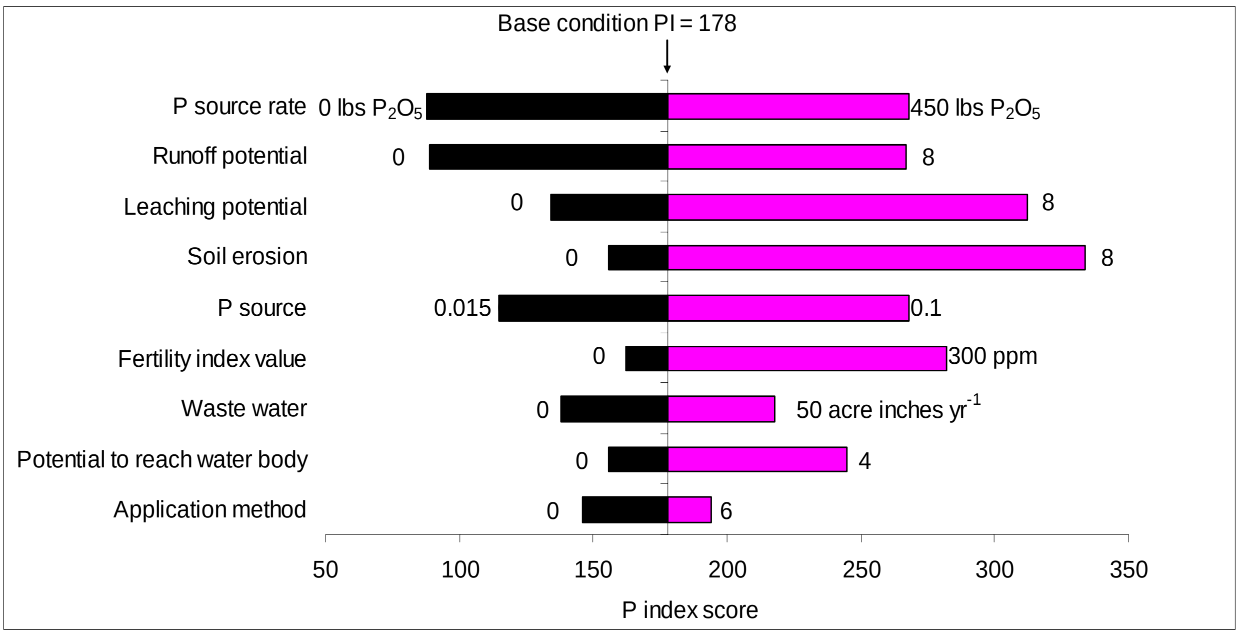


Figure 10-3. Tornado diagram of variables in the draft Florida P- index

Both PSAR and RP have the greatest impact, and are variables that can each reduce the P Index score to < 100 when other variables are at baseline values. Changes in the SE, FIV, and PWB are not capable of reducing the score below 150 (forcing P-based management), if other variables are at baseline. When other variables are at baseline values, the minimum score achievable by reducing SE and PWB is 156 while FIV can only reduce the score to 162. Thus, the P Index score that will allow N-based management (< 150 P Index score) is not achievable by singularly managing SE, PWB, or FIV.

The FIV (or soil test P), which has the lowest sensitivity coefficient, has a greater swing (i.e impact on the P Index score) than AM, PWB, and WWA. Thus, the FIV (or STP), though not as sensitive as other variables, could singularly increase the score to 282. However, if other variables are at baseline, the P Index score can not fall below 162 by simply reducing the STP.

Among the transport variables, RP has the greatest sensitivity coefficient, but not the greatest impact. The limit to its impact results from constraints by the domain limits allowed in the draft P Index. Similar constraints on the domain also limit the impacts of other variables with discrete ratings. Thus, LP and SE both have similar impacts on P Index score (swing = 178) as RP. However, unlike with RP, both LP and SE can not be each managed to reduce the P Index score below 90, when other variables are at baseline.

The PSA is also limited by the domain limit, and can swing the P Index score between 115 and 268. PWB can swing the score between 156 and 245, and the most limited swing was observed in AM (146 – 194).

Management involving two or more variables can lower the score below the lower limits of the swing for individual variables. For example, if no waste water is applied, the score is reduced from the 178 (base condition value) to 98. However, the P Index score can be further lowered to <80 if biosolids are also used instead of manure as the P-source, and lowered further, if the biosolids are incorporated immediately following application.

The effects of the variable sensitivity coefficients and swing on the P Index can be categorized by the matrix of the normalized coefficients and the swing (Fig. 10-4). For comparison, normalized values of related variables from the Pennsylvania P Index and the original Lemunyon and Gilbert P Index (1993), as calculated by Brandt and Elliott (2005), were included in Fig. 10-4.

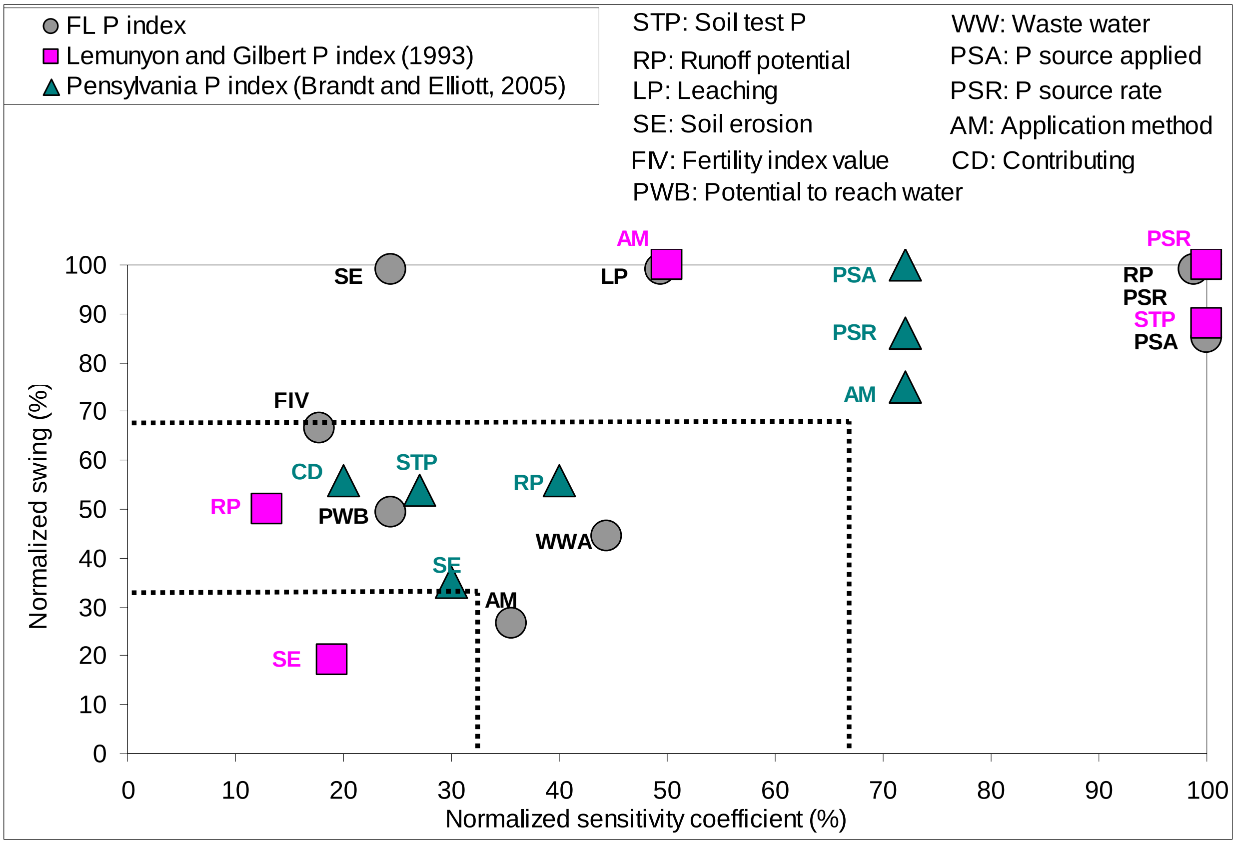


Figure 10-4. Nominal range sensitivity analysis matrix of the draft Florida P Index.

The variables are grouped by sensitivity and P Index score impacts into high (normalized coefficient and/or swing > 67%), intermediate (normalized coefficient and/or swing > 33%, but < 67%), and low (normalized coefficient and/or swing < 33%) categories. Five variables in the draft Florida P Index, PSAR, PSA, RP, LP, and SE fell into the high impact category. The remaining four variables, FIV, AM, WWA, and PWB, fell into the intermediate category. None of the variables in the draft Florida P Index fell within the low category, emphasizing the importance of all nine variables.

The PSAR was categorized as a high impact variable in all three P-Indices (Florida, Pennsylvania, and the original Lemunyon and Gilbert P Index). The PSA is included in the Pennsylvania and Florida P Index, but not in the original Lemunyon and Gilbert P Index, and is categorized as a high impact variable in both the Pennsylvania index and draft Florida P Index. The high impact observed justifies the inclusion of the P-source variable in the P-Indices of both Florida and Pennsylvania. The high impact of RP reflects the effect of high water table conditions in Florida that promote substantial runoff. Other important variables (high category) in Florida are LP (included in Florida P Index, but not in the Pennsylvania or in original Lemunyon and Gilbert P Indices) and SE (included in Florida and Pensylvania P Indices, but not in original Lemunyon and Gilbert P Index). The high impact category of SE results from the greater swing given to the variable in the draft Florida P Index. Thus, the domain (0-8) may need to be revised (lowered), e.g., to 0-4, or as justified by experimental data. Application method fell into the medium category in the Florida P Index, unlike in the Pennsylvania and original Lemunyon and Gilbert P-Indices, where the variable was categorized as high. The lesser impact of AM in the Florida than in the Pennsylvania and Lemunyon and Gilbert P-Indices may be related to the local conditions of Florida soils. Surface application, or incorporation, of P-sources may have little impact on P loss in Florida sands with high water tables and significant subsurface movement. However, in the greater P-sorbing Pennsylvania soils, incorporation of the P-source may significantly reduce P loss as compared to surface application, and result in greater impacts of AM. The FIV (or soil test P), a high impact variable in the original Lemunyon and Gilbert P- Index, was categorized as a medium impact variable in both the Florida and Pennsylvania P-Indices. The ranking is consistent with research studies indicating reduced impact of STP on P losses when other variables are considered (Pierson et al., 2001; Eghball and Gilley, 2001; DeLaune et al., 2002; Brandt and Elliott, 2003). PWB (or "contributing distances" in Pennsylvania P Index), are also categorized as medium impact variables in both the Florida and Pennsylvania P-Indices.

Sensitivity of the Draft Florida P Index Model to P Management

Apart from assisting the modeler in studying the impacts of the variables on the P Index score, another practical use of sensitivity analysis is evaluating P management strategies. Evaluation of impact management strategies on P losses is illustrated the following hypothetical question. How much can the P Index score be reduced if the management strategy is to reduce the rating of any one variable by half?

Figure 10-5 shows how much the score could be reduced when each variable is reduced by 50%, keeping all other variables at baseline.

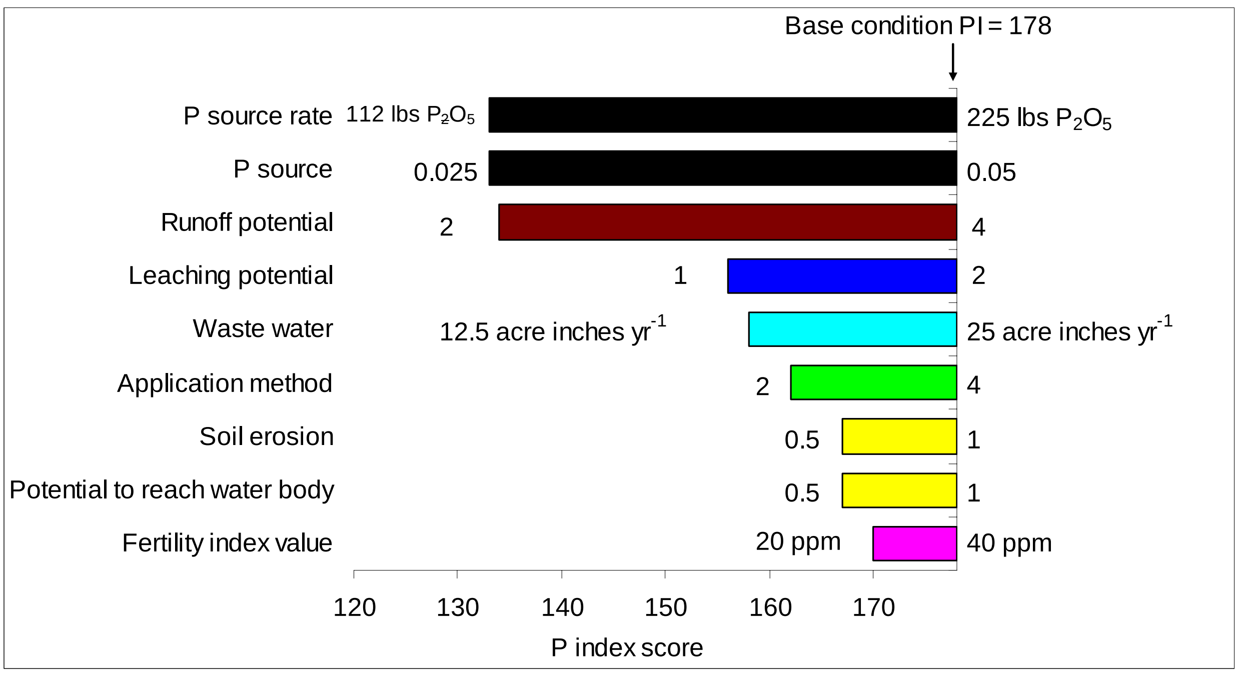


Figure 10-5. Draft Florida P Index scores associated with a 50% reduction in each input factor when other factors are held at baseline values

Reduction of PSAR from baseline 225 lbs P_2O_5 (110 kg P ha^{-1}) to 112 lbs P_2O_5 (55 kg P ha^{-1}; P-based) can reduce the PI score from 178 baseline value to 133. However, better P-management could be achieved by applying biosolids at 225 lbs P_2O_5 (P Index score = 115) than applying manure at 225 lbs P_2O_5 (P Index score = 178). Reduction of RP from high to medium rating gave the greatest reduction in P score (32). However, the cost of reducing RP can be prohibitive. Using biosolids instead of manure as a management practice could be easier, more economical, and reduces the score to as low as 115.

Sensitivity of the Draft Florida P Index Model to P-Source and P-Source Rate

The second hypothetical case examines the effects of different P-sources and P-source application rates on the P Index score. Kirton ranch field study data were used to study the sensitivity of the draft Florida P Index model to P-source and PSAR. The field study involved applying four P-sources at two rates (P-based and N-based) to plots in a landscape with similar SE, RP, LP, PWB, FIV, and AM, with no waste water applied (Table 10-4). The P-source coefficients in the draft Florida Index and the PWEP-based coefficients recommended in Chapter 8 were each used to compute the P index scores.

Applying manure or TSP at a P-based rate yielded a score of 83, and indicated the field had a medium P vulnerability category. However, the same field was categorized as low vulnerability when biosolids are applied at P-based rate. Applying biosolids at N-based rates increases the field rating back into the medium category. If manure is applied at an N-based rate, the field reaches a very high vulnerability rating and remedial action is required. Using the PWEP-based coefficients, the P Index values categorized P-based rates of all organic sources of P to low P loss vulnerability. The low category rating is consistent with low P harzards associated with the P-based rate and support the PWEP as a better coefficient than the source coefficients in the draft P Index. However, at the N-based rate, the scores range from 77 (medium category) for Pompano biosolids to 177 (high category) for TSP. The sensitivity analysis can serve as a very useful nutrient management tool for farmers, nutrient managers, and regulators.

Table 10-4. Draft Florida P Index scores of plots treated with four P-sources at two P rates in the field

Factors	Variable	<----Manure--->		Boca Raton biosolids		Pompano biosolids		<------TSP-------->	
		P-based	N-based	P-based	N-based	P-based	N-based	P-based	N-based
P-source	P rate (lbs P_2O_5)	80	573	80	646	80	556	80	180
	P-source coefficient (FPSC)	0.05	0.05	0.015	0.015	0.015	0.015	0.05	0.05
	P-source coefficient (PWEP-based)	0.046	0.046	0.055	0.055	0.012	0.012	0.084	0.084
	P-source multiplier (FPSC)	4	28.7	1.2	9.7	1.2	8.3	4	9
	P-source multiplier (PWEP)	1.44	10.3	0.96	7.8	0.32	2.2	6.72	15.1
	FIV@ 7ppm M-1P	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Application method (not incorporated)	6	6	6	6	6	6	6	6
	Waste water (not applied)	0	0	0	0	0	0	0	0
Transport	Soil Erosion	1	1	1	1	1	1	1	1
	Runoff potential	2	2	2	2	2	2	2	2
	Leaching potential	4	4	4	4	4	4	4	4
	Potential to reach water body	1	1	1	1	1	1	1	1
P Index value		83	280	60	128	60	117	83	123
P Index value (PWEP-based)		70	150	66	127	60	77	105	172
Generalized interpretation of P Index result		Medium	Very high	Low	Medium	Low	Medium	Medium	Medium

Summary and Conclusions

A sensitivity analysis of the Florida P Index identified all nine variables in the model as important. The variables fell into either the medium (FIV, AM, WWA, and PWB) or high (PSA, PSAR, RP, LP, and SE) impact category. None of the variables is redundant or impart low impacts. Experimental data are needed to assess the relative impacts of the nine variables on P loss. Study is also needed to evaluate the consistency of the variable impacts on P loss, and their impacts on P Index scores.

Most variable categories are consistent with other state P-Indices (Pennsylvania and the original Lemunyon and Gilbert P Index). The PSA and PSAR are categorized as high impact variables, and SE, PWB, and FIV categorized as medium impact variables by both Florida P Index and Pennsylvania P Index.

Immediate research addressing high impact variables is recommended. The wide range of P-sources available for land application, which have been reported to differ in solubility and P losses, may be better accounted for by more than the current three ratings (0.1 for waste water, 0.05 for manure and TSP, and 0.015 for biosolids). The use of PWEP-based coefficients recommended in Chapter 8 should be considered. Impacts of WWA could also be integrated into the P-sources variable, rather than being repeated as a variable under WWA amounts. Other questions raised by the sensitivity analysis that need to be validated by experimental data are:

- Is soil erosion so important in Florida that a wider swing should be assigned and should erosion be categorized as high impact variable, unlike in other P-Indices (Pennsylvania and the original Lemunyon and Gilbert P Index), where the variable is categorized as medium or low impact?
- Is application method, categorized as having only a medium impact in Florida, consistent with the high impact categorization in the original Lemunyon and Gilbert P Index?

The use of continuous, rather than discrete ratings should be considered, where possible. Continuous variables provide smoother model output and avoid subjectivity inherent to assigning ratings to a particular variable (Elliott et al., 2006). Continuous ratings could be used for SE by multiplying the SE values in tons per acre by 0.533. The factor, 0.533 will give equivalent ratings (0 – 8) for erosion between 0 and 15 tons acre^{-1} (as in Florida P Index) and greater ratings when erosion is ≥15 tons $acre^{-1}$. Other variables that could be assigned continuous ratings are PSA (Elliott et al., 2006), and PWB. However, assigning continuous ratings to these variables should be based on data from studies on Florida soils.

CHAPTER 11
MANAGEMENT OF PHOSPHORUS SOURCES AND WATER TREATMENT RESIDUALS (WTR) FOR ENVIRONMENTAL AND AGRONOMIC BENEFITS

Co-application of WTR with different P-sources has potential as a BMP to reduce the environmental hazard associated with excess soil P in low P-sorbing coastal plain sands, without negative agronomic impact. Understanding how different P-sources, source application rates, and WTR affects soil P loss and agronomic returns will enhance sound management of the wastes for agronomic and environmental benefits. Thus the objective of the study was to evaluate the environmental and agronomic impacts of different P sources and WTR and to determine the rate of P-sources and WTR that optimize environmental and agronomic benefits.

Impacts of P-sources, source application rates, and WTR on P loss and availability to plants were evaluated in glasshouse and rainfall simulation studies and validated using results from a 2-year field study with similar treatments. Within a week of incorporating the P-sources and WTR with a low P-sorbing sandy soil in the glasshouse study, the degree of P saturation (DPS) was reduced and, in most cases, was below the 25% threshold value suggested for Florida soils (Nair et al., 2004). The capacity of the soil to retain P and prevent P migration and loss as measured by soil P storage capacity (SPSC) values was also increased. Both DPS and SPSC values showed dramatic improvement in the P sorption property of the soil following amendment with WTR. Similar improvements in the soil DPS and SPSC values were observed in all the surface A-horizon samples obtained from the field sampled periodically in the 2-year study. However, the impacts of the WTR on soil DPS and SPSC values depend on the application rates of the P-sources and WTR. Generally, greater amounts of WTR are required for N-based P-source application rates than for P-based application rates to achieve similar sorption properties.

Improved soil P-sorption was accompanied by reduced soil soluble P and groundwater P concentrations. Both WEP and ISP values of soil samples taken during the glasshouse study and samples obtained from the A-horizon in the field study were reduced in WTR treatments compared to untreated soils. The reduction in soil soluble P following addition of WTR was reflected in reduced losses of P in runoff and leachate in the rainfall simulation study. Also and most importantly, the P concentrations of groundwater samples obtained in the field were smaller in the WTR treatments than in untreated soils. The impacts of surface-applied WTR were observed in groundwater samples taken both above and below the spodic horizon during the field study, regardless of P-source or source application rate, and P concentrations were less than those measured in the control treatments. The greater soil total Al concentrations of the Al-WTR treatments neither increased groundwater Al nor plant Al concentrations.

The P-sources and source application rates affected soil soluble P concentrations and P losses. Generally, greater soil WEP values and, hence soluble P concentrations, were observed at N-based rates than P-based rates in the glasshouse study. Also, there were greater P losses from N-based treatments than P-based treatments in the runoff, leachate, and TP (runoff + leachate) of each P-source in the absence of WTR. However, the P loss from the TSP treatments applied at a P-based rate was similar or greater (depending on the source) than the losses observed at N-based rates of the organic sources of P. Thus, the P hazard from applying organic sources at N-based rates was lower than, or similar to, that observed at P-based rate of the mineral P-source. Also, the P loss from applying a moderate water soluble P biosolids (Pompano biosolids) at N-based rates was not greater than the P loss from a high water soluble P organic source at P-based rates. Thus, P losses can be controlled (without applying WTR) by using lower water soluble P materials. The collective results of the study suggest that environmental P hazards associated with high application rates (N-based rate) of P materials can be managed by either applying the P-source with WTR, or by using lower water soluble P-sources. The masses of bioavailable P (BAP) and TP loss were similarly affected by the P-sources and followed the same trend as PWEP values of the sources (PWEP values in parentheses): TSP (84%) > manure (18%) > Boca Raton biosolids (12%) > Pompano biosolids (4%). Regression of BAP loss with source application rate ($r^2 = 0.27$) was improved by accounting for P-sources solubility differences with the draft Florida P Index coefficients ($r^2 = 0.54$), P-source coefficients (PSC) values suggested by Elliott et al. (2006) ($r^2 = 0.77$), and PWEP values of the sources ($r^2 = 0.81$). Use of a coefficient based on PWEP of the P-source is suggested as a means of differentiating P loss potentials of different P-sources, and is recommended as alternative to coefficients currently used in the draft Florida P Index. The three coefficients suggested in the draft Florida P Index (coefficient = 0.05 for fertilizer and manure, 0.015 for all biosolids, and 0.10 for waste water), were insufficient to account for the wide variability in the P-sources. Default values for PWEP-based coefficients for different types of P-sources are suggested.

The agronomic impacts of the three managements approaches identified to reduce P loss (improving the soil sorption capacity by application of WTR, applying the P-sources at P-based rates, and use of lower water soluble P amendments) were tested. The applied Al-rich WTR, neither increased the groundwater Al concentrations, nor increased plant Al concentrations. Data from both the field and the glasshouse studies indicate no greater Al concentrations in plants grown in WTR-amended soils than in unamended soils. Amending soil with WTR could be a best management practice (BMP) to reduce the hazard associated with excess P from land-applied mineral and organic sources of P, even at high P loads associated with N-based source application rates. The soil P hazard will be reduced, if not eliminated, without negative agronomic impacts such as reduced plants yields or Al toxicity.

Applying WTR, even at 2.5%, to N-based rates treatments did not reduce plant yields in most cases. However, at P-based rates of P-source application, WTR of more than 1% reduced yields. The plant P concentrations were reduced by application of WTR, but at the N-based source application rate, with WTR, the P concentrations were sufficient for optimum plant growth. The plant yields at N-based rates with WTR were similar or greater than observed at the P-based rate of TSP without WTR in the glasshouse and the field studies.

A recommendation to apply WTR on a fixed oven dry basis could result in negative agronomic and or environmental impacts depending on WTR and the Al, P and Fe concentrations of the P-sources. Application rates of WTR based on a desired soil SPSC value ensure applying the amount of WTR needed to reduce excess P, while providing sufficient P for optimum plant growth. A SPSC value of zero (0 mg kg^{-1}) was identified as the critical point, above which plant P concentrations can be reduced sufficiently to reduce plant yields, and below which the potential for P loss increases. Results from the glasshouse and field studies show that the environmental hazard associated with excess P loads from N-based source applications are controlled by application of WTR without negative agronomic impacts.

The P-sources differed in potential for P loss and relative P phytoavailability (RPP). The RPP value of the moderate water soluble P, Pompano biosolids fell into the moderate phytoavailable biosolids category, whereas the high water soluble P Boca Raton biosolids RPP fell into the high category along with TSP. The RPP value of the moderate water soluble P, Pompano biosolids, and poultry manure also fell into the moderate relative phytoavailability category. Properties of manure that can account for the RPP could not be investigated because only one manure type (poultry manure) was used in this study. Results from the field study were consistent with the glasshouse studies in classifying P-sources into RPP categories.

The organic sources of P varied in RPP values in the field in a similar manner as the values observed in the glasshouse study. The field study RPP values of the Pompano biosolids and poultry manure agreed with the expected moderate phytoavailable biosolids class determined in the glasshouse study, and the Boca Raton biosolids RPP values from both studies were classified as high. A method proposed by Quebec Canada regulatory agency (CRAAQ, 2003; MENV 2003), which estimate % P availability values of organic sources of P from an empirical equation that accounts for select P-source characteristics, was not validated by either the greenhouse or the field data. Properties identified to account for the RPP values of biosolids are Total P concentration, NaOH-P and %solids. These properties could be the focus of further study into estimating RPP values of biosolids from their properties. Also further studies with varying types of manure will be needed to identify properties that could account for manure RPP.

Both the P-source and P transport potentials affect P loss from a watershed. The importance of the two factors on P loss is addressed in the P-Indices being developed by 47 states in the US. Sensitivity analysis of the draft Florida P Index was carried out to study the impacts of the variables and identify areas where future studies on P losses should be focused. The sensitivity analysis indicated that all nine variables in the FL model are important and fell into either the medium (FIV, AM, WWA, and PWB) or high (PSR, RP, LP, PSA, and SE) impact categories. None of the variables is redundant or of low impact. The variable categories are also consistent with other states P-indices (Pennsylvania and the original Lemunyon and Gilbert P Index).

Peculiar local conditions were well considered in the draft Florida P Index. However, contrary to widely-held expectations of greater leaching potential in Florida soils, runoff potential was identified as more important. The importance of runoff likely results from the high water table conditions that characterizes many FL soils, and reduces the vertical movement (leaching). However, on a relative scale (compared to other states), leaching is also important in Florida soils. Recommendations were made for studies into all the variables in the P Index and the use of continuous ratings for the variables wherever possible. Also the use of more than 3 variables to account for the wide spectrum of P-source solubilities is recommended, including source coefficients based on PWEP of the sources.

APPENDIX A
PUBLICATIONS ARISING FROM THE DISSERTATION

Oladeji, O.O., G.A. O'Connor, and S.R. Brinton. Effects of water treatment residual (WTR) on runoff and leachate phosphorus losses in a Florida sand (In preparation for publication in Journal of Environmental Quality).

Oladeji, O.O., J.B. Sartain, and G.A. O'Connor. (2006). Agronomic impact of land applied water treatment residuals (Submitted for publication in Soil Crop Science Society of Florida Proceedings).

Oladeji, O.O., G.A. O'Connor, and H.A. Elliott. Basis for estimating P-sources coefficients for the Florida P Index (In preparation for publication in Journal of Environmental Quality).

Oladeji, O.O., J.B. Sartain, and G.A. O'Connor. Application rates of phosphorus (P) sources and water treatment residuals (WTR) for agronomic and environmental benefits (In preparation for publication in Journal of Environmental Quality).

Oladeji, O.O., J.B. Sartain, and G.A. O'Connor. Land application of water treatment residual (WTR): Agronomic P efficiency and aluminum phytotoxicity (In preparation for publication in Communications in Soil Science and Plant Analysis).

Oladeji, O.O., J.B. Sartain, and G.A. O'Connor. Evaluation of soil test methods for Florida sand treated with different P-sources and WTR (In preparation for publication in Communications in Soil Science and Plant Analysis).

Oladeji, O.O., G.A. O'Connor, H.A. Elliott, and J.B. Sartain. Sensitivity analysis of Florida P Index (In preparation for publication in Journal of Soil and Water Conservation).

Oral Presentations

Oladeji, O.O., G.A. O'Connor, and J.B. Sartain. 2006. Effect of water treatment residuals (WTR) on runoff and leachate phosphorus losses in a Florida sand. Presented at the 2006 Annual meeting of the Southern Branch of Agronomy Society of America in Orlando, FL.

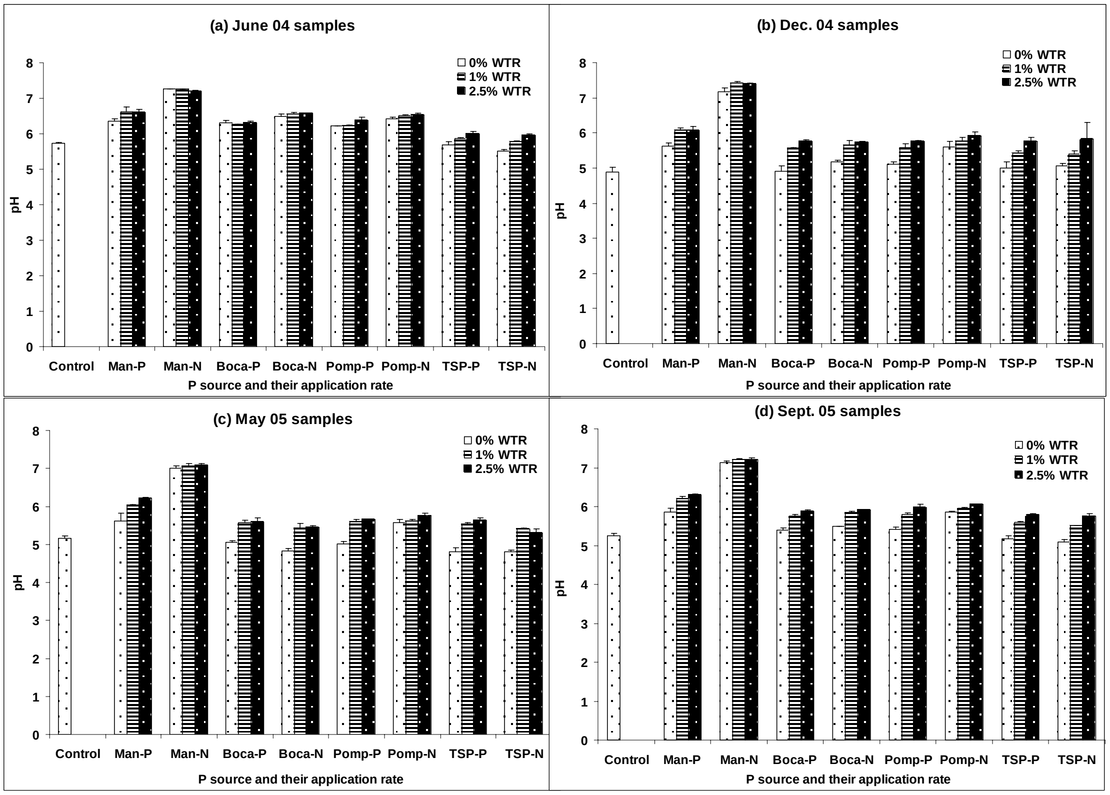
Oladeji, O.O., G.A. O'Connor, and J.B. Sartain. 2006. Basis for estimating P-source coefficients for the Florida P Index. Presented at Soil and Crop Science Society of Florida annual meeting 2006.

Oladeji, O.O., J.B. Sartain, and G.A. O'Connor. 2006. Application rate of water treatment residual (WTR) based on agro-environmental threshold. Presented at Soil and Crop Science Society of Florida annual meeting 2006.

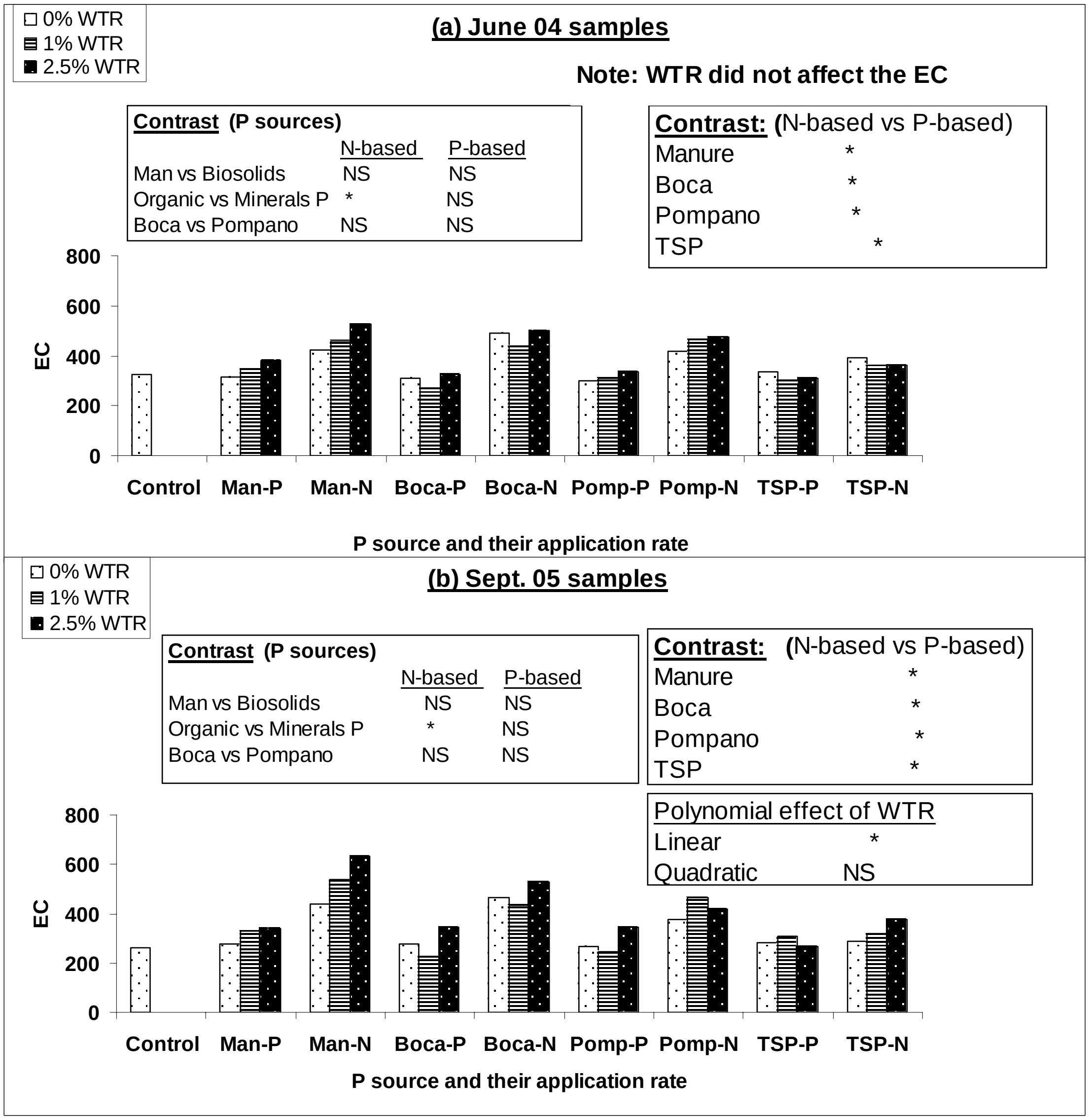
Oladeji, O.O., G.A. O'Connor, and J.B. Sartain. 2006. A methodology to account for P release potential from different sources of P. Presentation at Soil Science Society of America annual meetings, 2006.

Oladeji, O.O., J.B. Sartain, and G.A. O'Connor. 2005. Agronomic impact of land applied water treatment residuals: Soil test methods and application rates. Presented at Soil and Crop Science Society of Florida annual meeting, 2005.

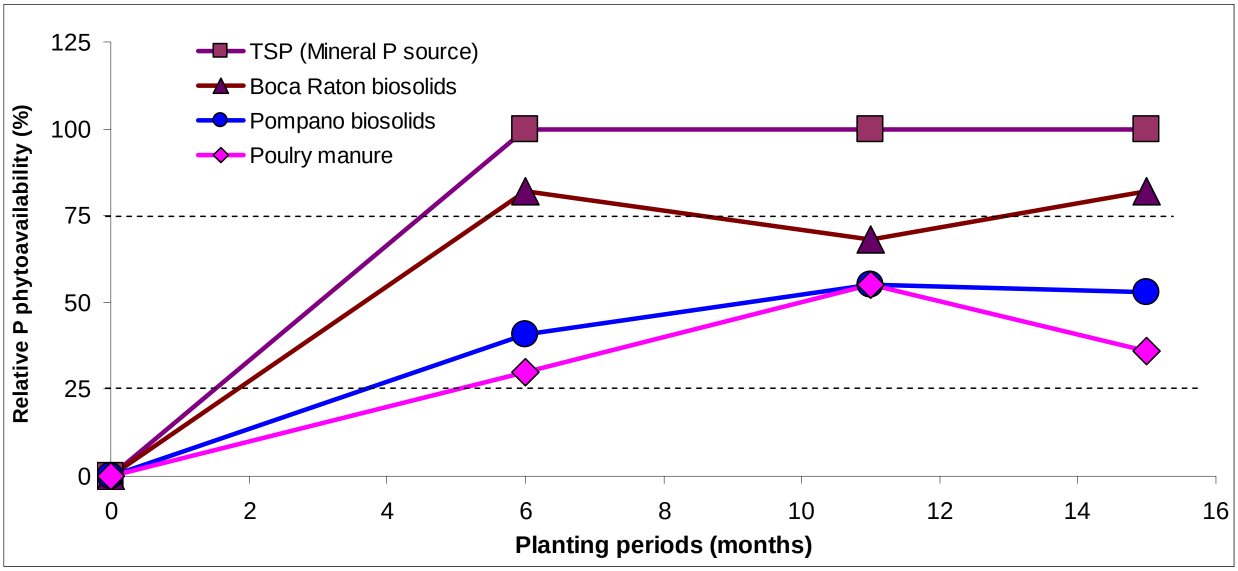
APPENDIX B
OTHER RELEVANT TABLES AND FIGURES



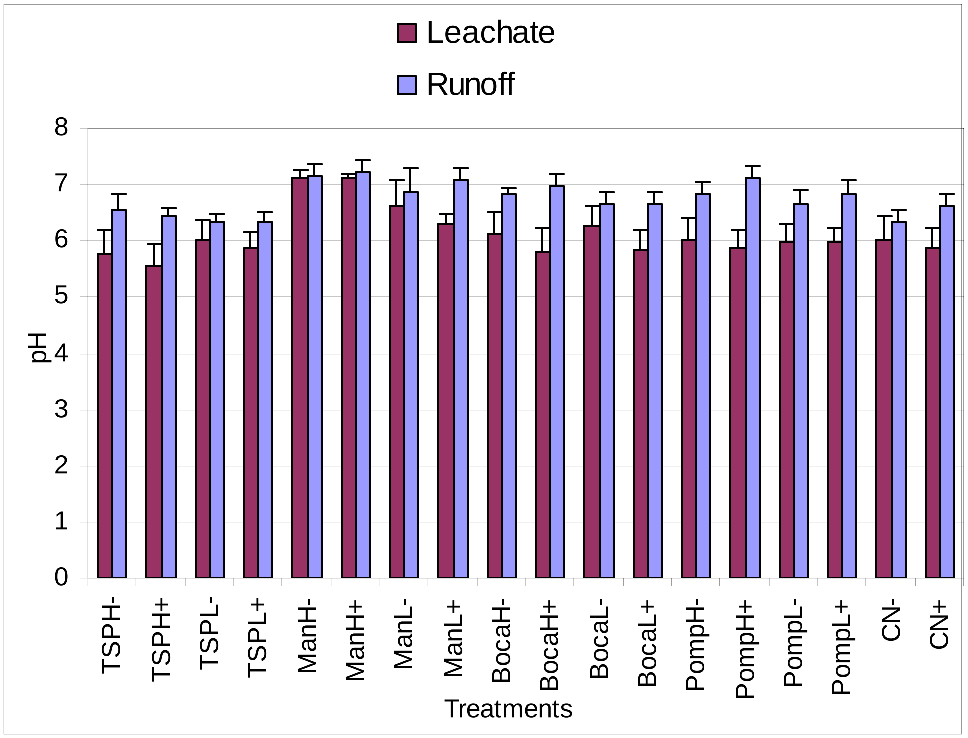
Appendix Figure B-1. The pH of soil samples taken during the glasshouse study



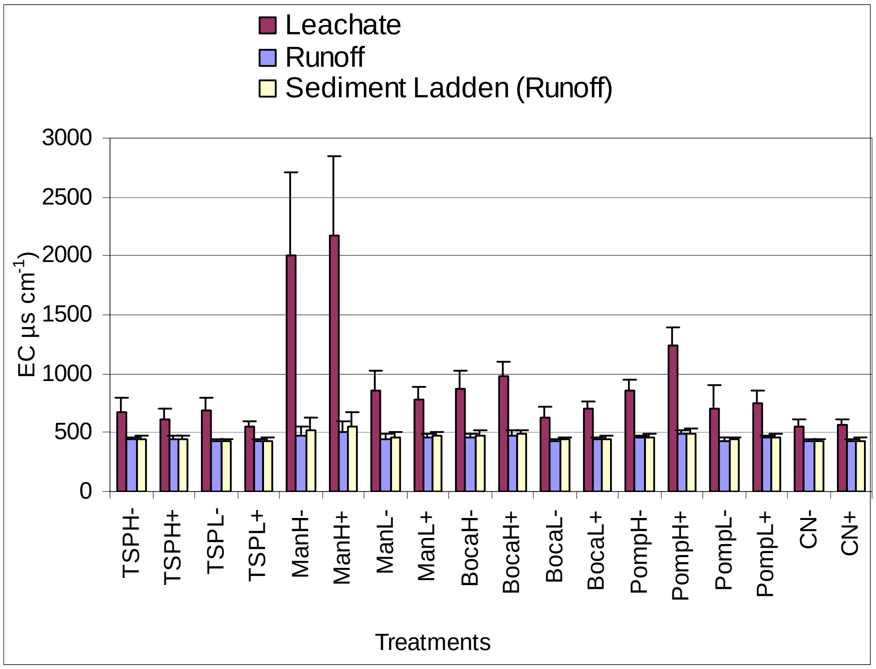
Appendix Figure B-2. The EC values (μs cm^{-1}) of time zero and time final soil samples taken during the glasshouse study. (* significant at 5%; NS is non significant at 5%)



Appendix Figure B-3. Effects of time on relative P phytoavailability (RPP) of the different P-sources during the glasshouse study.



Appendix Figure B-4. Runoff and leachate pH values of the treatments across the three runs and replicates during the rainfall simulation experiment (n = 6, error bars represent one standard error)



Appendix Figure B-5. Runoff and leachate EC values of the treatments across the three runs and replicates during the rainfall simulation experiment (n = 6, error bars represent one standard error)

Appendix Table B-1. Electric conductivity (µs cm^{-3}) values of soil samples taken during the glasshouse study.

P-source	P-source rate	WTR rate (0ven dry %)	Sampling periods			
			June '04	Dec. '04	May '05	Sept. '05
Control	--	--	324 ^{defg}	211 ^{cd}	249 ^{b}	261 ^{def}
Manure	P based	0	315 ^{defg}	265 ^{abcd}	258 ^{b}	279 ^{def}
		1	348 ^{bcdefg}	323 ^{abcd}	324 ^{ab}	331 ^{bcdef}
		2.5	380 ^{abcdefg}	394 ^{abcd}	245 ^{b}	340 ^{bcdef}
	N-based	0	424 ^{abcdefg}	573 ^{abc}	317 ^{ab}	438 ^{abcdef}
		1	458 ^{abcdef}	646 ^{a}	518 ^{ab}	540 ^{ab}
		2.5	528 ^{a}	599 ^{ab}	776 ^{a}	634 ^{a}
Boca Raton Biosolids	P based	0	310 ^{defg}	301 ^{abcd}	223 ^{b}	278 ^{def}
		1	270 ^{g}	258 ^{bcd}	153 ^{b}	226 ^{f}
		2.5	323 ^{defg}	301 ^{abcd}	407 ^{ab}	343 ^{bcdef}
	N-based	0	489 ^{abc}	318 ^{abcd}	587 ^{ab}	464 ^{abcde}
		1	439 ^{abcdef}	325 ^{abcd}	534 ^{ab}	432 ^{abcdef}
		2.5	499 ^{ab}	557 ^{abc}	523 ^{ab}	526 ^{abc}
Pompano Biosolids	P based	0	301 ^{fg}	189 ^{cd}	323 ^{ab}	269 ^{def}
		1	308 ^{efg}	228 ^{bcd}	205 ^{b}	247 ^{ef}
		2.5	333 ^{cdefg}	348 ^{abcd}	342 ^{ab}	344 ^{bcdef}
	N-based	0	418 ^{abcdefg}	415 ^{abcd}	300 ^{ab}	377 ^{bcdef}
		1	465 ^{abcde}	546 ^{abc}	392 ^{ab}	467 ^{abcd}
		2.5	472 ^{abcd}	491 ^{abcd}	291 ^{ab}	418 ^{abcdef}
TSP	P based	0	336 ^{bcdefg}	257 ^{bcd}	261 ^{b}	284 ^{def}
		1	299 ^{fg}	387 ^{abcd}	232 ^{b}	306 ^{def}
		2.5	311 ^{defg}	302 ^{abcd}	187 ^{b}	266 ^{def}
	N-based	0	391 ^{abcdefg}	159 ^{d}	314 ^{ab}	288 ^{def}
		1	360 ^{bcdefg}	422 ^{abcd}	179 ^{b}	320 ^{cdef}
		2.5	362 ^{bcdefg}	282 ^{abcd}	620 ^{ab}	376 ^{bcdef}

Means (n = 3) of treatments during the same sampling period follow by the same letter are not different at 5% significance level

Appendix Table B-2. Bahiagrass and ryegrass yields, P concentrations, and P uptake values from different treatments during the glasshouse study.

P-source	Rate	WTR (%)	First Bahiagrass Dry Matter (Mg ha^{-1})	First Bahiagrass P concn. (g kg^{-1})	First Bahiagrass P uptake (kg ha^{-1})	Ryegrass Dry Matter (Mg ha^{-1})	Ryegrass P concn. (g kg^{-1})	Ryegrass P uptake (kg ha^{-1})	Second Bahiagrass Dry Matter (Mg ha^{-1})	Second Bahiagrass P concn. (g kg^{-1})	Second Bahiagrass P uptake (kg ha^{-1})
Control			5.66 ± 0.25†	1.94 ± 0.12	11.0 ± 0.7	2.49 ± 0.12	2.03 ± 0.15	5.07 ± 0.50	3.27 ± 0.46	1.59 ± 0.11	5.24 ± 0.96
Manure	P-based	0	7.12 ± 1.18	3.03 ± 0.65	21.2 ± 2.4	3.38 ± 0.05	2.78 ± 0.13	9.41 ± 0.51	3.28 ± 0.07	2.65 ± 0.08	8.71 ± 0.45
		1	6.35 ± 0.60	1.79 ± 0.19	11.4 ± 1.7	3.37 ± 0.18	2.11 ± 0.08	7.12 ± 0.57	3.21 ± 0.18	2.57 ± 0.15	8.20 ± 0.11
		2.5	6.08 ± 0.22	1.73± 0.04	10.5 ± 0.5	3.32 ± 0.21	1.82 ± 0.07	6.09 ± 0.61	3.02 ± 0.26	1.98 ± 0.16	5.93 ± 0.47
	N-based	0	5.13 ± 0.85	3.84± 0.24	19.8 ± 4.1	4.50 ± 0.04	4.33 ± 0.09	19.4 ± 0.4	3.86 ± 0.31	2.76 ± 0.35	10.4 ± 0.71
		1	4.39 ± 0.58	1.73± 0.41	7.75 ± 2.86	4.41 ± 0.19	2.72 ± 0.32	12.0 ± 1.6	4.29 ± 0.44	2.39 ± 0.20	10.3 ± 1.6
		2.5	4.12 ± 0.66	1.87± 0.12	7.67 ± 1.03	4.23 ± 0.13	2.30 ± 0.26	9.77 ± 1.30	3.83 ± 0.08	2.50 ± 0.13	9.55 ± 0.35
Boca Biosolids	P-based	0	6.77 ± 1.32	3.90± 0.20	26.2 ± 4.3	3.11 ± 0.12	2.94 ± 0.26	9.10 ± 0.54	3.59 ± 0.09	2.23 ± 0.10	7.98 ± 0.18
		1	5.71 ± 0.79	1.83± 0.27	10.3 ± 0.5	2.82 ± 0.04	2.03 ± 0.11	5.72 ± 0.36	3.19 ± 0.08	2.63 ± 0.41	8.34 ± 1.16
		2.5	5.43 ± 1.18	1.77± 0.17	9.58 ± 1.85	2.93 ± 0.18	1.99 ± 0.21	5.87 ± 0.92	2.92 ± 0.10	1.99 ± 0.13	5.79 ± 0.31
	N-based	0	8.17 ± 0.62	6.43± 0.12	52.6 ± 0.6	3.83 ± 0.12	5.98 ± 0.75	23.0 ± 3.2	5.56 ± 0.38	4.38 ± 0.55	24.5 ± 4.2
		1	7.42 ± 0.92	3.60± 0.43	27.0 ± 6.6	4.12 ± 0.36	4.19 ± 0.39	17.5 ± 3.10	5.43 ± 0.35	3.45 ± 0.16	18.6 ± 0.6
		2.5	7.01 ± 1.06	2.80± 0.51	19.8 ± 5.9	4.22 ± 0.24	3.09 ± 0.45	13.1 ± 2.32	5.65 ± 0.39	3.26 ± 0.24	18.4 ± 1.8
Pompano Biosolids	P-based	0	6.51 ± 1.05	2.74± 0.14	17.8 ± 3.0	3.14 ± 0.08	2.69 ± 0.22	8.48 ± 0.85	3.52 ± 0.10	2.18 ± 0.23	7.62 ± 0.60
		1	5.80 ± 0.51	1.82± 0.12	10.6 ± 0.6	3.08 ± 0.21	2.11 ± 0.05	6.49 ± 0.50	3.12 ± 0.20	2.01 ± 0.29	6.21 ± 0.87
		2.5	5.40 ± 0.39	1.67± 0.15	8.98 ± 0.70	2.94 ± 0.12	1.89 ± 0.19	5.58 ± 0.75	3.51 ± 0.01	1.95 ± 0.27	6.85 ± 0.92
	N-based	0	6.86 ± 0.62	4.43± 0.48	30.2 ± 2.2	3.62 ± 0.17	5.13 ± 0.19	18.5 ± 0.9	4.81 ± 0.46	3.57 ± 0.24	17.0 ± 1.2
		1	6.56 ± 1.38	2.47± 0.13	16.3 ± 3.8	3.83 ± 0.04	3.09 ± 0.30	11.8 ± 1.0	4.19 ± 0.17	3.20 ± 0.19	13.5 ± 1.2
		2.5	6.54 ± 0.76	2.36± 0.08	15.4 ± 2.0	3.79 ± 0.16	2.67 ± 0.23	10.1 ± 1.2	3.86 ± 0.17	3.32 ± 0.32	12.7 ± 0.9
TSP	P-based	0	6.29 ± 0.37	3.60± 0.29	22.6 ± 1.3	3.07 ± 0.11	6.28 ± 3.75	8.87 ± 1.34	3.43 ± 0.34	2.06 ± 0.10	7.03 ± 0.53
		1	5.77 ± 0.36	1.82± 0.17	10.5 ± 0.8	3.04 ± 0.10	2.20 ± 0.18	6.65 ± 0.36	2.85 ± 0.24	2.18 ± 0.20	6.16 ± 0.53
		2.5	4.82 ± 0.64	1.55± 0.19	7.38 ± 0.19	3.31 ± 0.28	1.90 ± 0.24	6.34 ± 1.07	2.64 ± 0.03	1.98 ± 0.16	5.23 ± 0.49
	N-based	0	6.79 ± 1.18	5.31± 0.68	36.0 ± 7.1	3.28 ± 0.07	3.59 ± 0.43	11.7 ± 1.4	3.38 ± 0.40	2.68 ± 0.12	9.07 ± 1.19
		1	5.67 ± 1.11	1.99± 0.23	11.1 ± 1.7	3.40 ± 0.20	2.57 ± 0.08	8.73 ± 0.54	2.50 ± 0.13	2.35 ± 0.19	5.83 ± 0.31
		2.5	5.88 ± 0.94	1.95± 0.16	11.4 ± 0.9	3.23 ± 0.20	2.40 ± 0.10	7.77 ± 0.72	2.60 ± 0.51	1.95 ± 0.22	4.97 ± 0.86

† means (n = 3) ± Standard deviation

Appendix Table B-3. Varying measures of soil test P at planting of the first bahiagrass crop (June 2004), the ryegrass crop (December 2004), and the second bahiagrass crop(May 2005) during the glasshouse study

P-source	P rate	WTR rate (%)	<----------------[‡]WEP---------------->			<--------------------[§]ISP----------------->			<----------------[¶]M-1P------------------->		
			June 2004	Dec. 2004	May 2005	June 2004	Dec. 2004	May 2005	June 2004	Dec. 2004	May 2005
Control	--	--	[†]2.88±0.19	3.01 ± 0.33	1.14 ± 0.07	3.11 ± 0.48	3.87 ± 0.23	1.35 ± 0.22	6.40 ± 0.35	2.93 ± 0.58	2.24 ± 0.39
Manure	P-based	0	6.35±1.58	8.47 ± 0.56	1.82 ± 0.16	9.04 ± 0.68	8.16 ± 0.43	2.23 ± 0.61	15.8 ± 0.1	14.38 ± 0.35	5.93 ± 1.14
		1	3.54±0.18	2.23 ± 0.26	1.21 ± 0.11	6.04 ± 0.36	4.91 ± 0.22	2.12 ± 0.20	23.7 ±5.3	14.70 ± 1.23	13.6 ± 0.6
		2.5	2.73±0.44	1.90 ± 0.12	0.97 ± 0.03	3.08 ± 0.72	4.37 ± 0.13	1.78 ± 0.20	29.7 ± 1.8	19.18 ± 1.22	20.2 ± 2.1
	N-based	0	18.7±0.78	11.47 ± 1.17	4.99 ± 1.63	23.3 ± 1.8	25.52 ± 3.26	11.7 ± 3.8	63.5 ± 8.1	67.53 ± 2.35	54.0 ± 3.9
		1	11.3±0.7	5.08 ± 1.07	2.83 ± 0.07	16.3 ± 0.6	13.09 ± 0.64	8.12 ± 0.79	69.5 ± 8.0	67.53 ± 3.58	59.6 ± 2.4
		2.5	5.78±0.30	3.37 ± 1.00	2.88 ± 1.35	11.7 ± 0.3	9.26 ± 0.42	7.77 ± 2.19	69.3 ± 11.7	66.08 ± 2.16	57.7 ± 1.9
Boca Raton Biosolids	P-based	0	6.53±0.29	4.43 ± 0.83	2.06 ± 0.17	7.37 ± 0.83	8.00 ± 1.07	2.90 ± 0.30	23.7 ± 6.6	10.49 ± 1.73	6.92 ± 0.78
		1	3.80±0.45	1.43 ± 0.32	1.15 ± 0.14	4.09 ± 0.53	5.24 ± 0.16	2.24 ± 0.11	24.8 ±7.6	14.97 ± 0.61	14.1 ± 0.2
		2.5	2.63±0.32	1.17 ± 0.34	0.97 ± 0.05	3.79 ± 0.47	4.28 ± 0.38	1.90 ± 0.11	31.8 ±7.1	18.36 ± 2.58	21.5 ± 1.2
	N-based	0	41.4±2.3	21.73 ± 0.27	17.8 ± 1.5	52.4 ± 5.1	32.79 ± 3.79	26.0 ± 1.1	164 ±13	67.94 ± 4.79	55.7 ± 3.9
		1	20.8±1.0	6.51 ± 0.44	3.19 ± 0.33	35.9 ±2.0	17.55 ± 0.83	10.4 ± 1.0	147 ±8	69.55 ± 2.35	64.5 ± 0.3
		2.5	15.4±0.6	3.65 ± 0.41	1.74 ± 0.03	20.9 ±1.9	11.07 ± 0.47	11.8 ± 4.7	148 ±18	82.71 ± 7.24	72.3 ± 1.2
Pompano Biosolids	P-based	0	3.94±0.41	5.14 ± 1.39	2.05 ± 0.01	4.34 ± 0.84	6.33 ± 0.52	3.46 ± 0.52	16.6 ±1.7	8.77 ± 0.42	7.50 ± 1.01
		1	2.59± 0.32	1.40 ± 0.29	1.03 ± 0.10	3.32 ± 0.18	4.54 ± 0.22	2.78 ± 0.83	20.5 ±1.6	11.87 ± 1.61	11.4 ± 0.8
		2.5	1.96± 0.05	1.26 ± 0.26	0.93 ± 0.05	2.72 ± 0.19	4.00 ± 0.10	2.12 ± 0.38	26.9 ±1.6	17.93 ± 1.20	16.0 ± 0.7
	N-based	0	6.37± 0.40	9.04 ± 1.67	4.70 ± 0.58	11.9 ±0.6	15.05 ± 2.59	14.0 ± 4.6	66.5 ±4.9	48.75 ± 6.92	35.8 ± 5.0
		1	3.77± 0.65	6.67 ± 1.50	1.49 ± 0.04	7.96 ± 0.13	8.38 ± 0.53	4.75 ± 0.72	64.3 ±12.3	49.55 ± 4.84	50.2 ± 6.3
		2.5	2.63± 0.34	3.88 ± 1.36	1.20 ± 0.07	5.43 ± 0.18	6.08 ± 0.19	3.79 ± 0.51	65.2 ±7.2	52.19 ± 2.01	41.7 ± 3.8
TSP	P-based	0	12.2 ± 4.1	8.61 ± 0.40	1.81 ± 0.29	10.4 ± 1.11	7.43 ± 0.67	2.69 ± 0.40	23.5 ± 5.7	10.73 ± 1.60	5.01 ± 0.72
		1	3.68± 1.75	4.60 ± 0.51	1.11 ± 0.06	4.47 ± 0.66	4.68 ± 0.24	1.78 ± 0.19	24.4 ± 6.5	11.63 ± 0.52	10.4 ± 0.3
		2.5	1.95± 0.51	4.67 ± 0.19	0.94 ± 0.15	3.02 ± 0.51	3.98 ± 0.13	1.80 ± 0.33	24.7 ± 6.9	15.08 ± 1.79	17.3 ± 2.7
	N-based	0	19.4 ± 2.7	11.42 ± 1.29	4.16 ± 0.75	20.8 ± 0.5	11.16 ± 1.11	5.33 ± 0.39	46.8 ± 15.6	16.00 ± 0.41	11.2 ± 2.2
		1	8.45 ±1.56	4.45 ± 0.84	1.34 ± 0.05	12.4 ± 1.5	5.54 ± 0.39	3.24 ± 0.28	37.6 ± 6.5	17.13 ± 0.60	17.1 ± 1.5
		2.5	3.90± 0.40	4.19 ± 0.40	1.32 ± 0.41	6.97 ± 0.6	4.83 ± 0.43	8.10 ± 6.29	41.2 ± 0.5	19.97 ± 3.67	16.3 ± 5.4

[†] means (n = 3) ± Standard deviation
[‡] Water extractable P
[§] Iron strip P
[¶] Mehlich 1P

Appendix Table B-4. Degree of phosphorus saturation (DPS) values of soil samples between June 2003 and December 2004 during the field study. (All values are in %)

Treatments	June 2003 (0-5cm)	Jan 2004 (0-5cm)	Dec. 2004 (0-5cm)	March 2004 (0-15cm)	Dec 2004 (0-15cm)
Controls	‡62 ab	52 ab	8 gh	180 a	79 abc
Manure-N, no WTR	117 ab	95 a	33 cde	185 a	57 d
Manure-P, no WTR	88 ab	55 ab	25 def	186 a	61 cd
Manure-N, WTR	31 ab	18 ab	10 fgh	43 c	14 e
Manure-P, WTR	15 b	14 ab	6 gh	30 c	14 e
Boca-N, no WTR	94 ab	65 ab	76 a	43 c	93 a
Boca-P, no WTR	50 ab	65 ab	38 bcd	78 bc	82 ab
Boca-N, WTR	33 ab	19 ab	21 efg	26 c	13 e
Boca-P, WTR	19 ab	41 ab	11 fgh	31 c	14 e
Pompano-N, no WTR	137 a	86 ab	52 b	52 c	77 abcd
Pompano-P, no WTR	57 ab	60 ab	37 bcde	58 c	72 bcd
Pompano-N, WTR	13 b	13 b	7 gh	31 c	6 e
Pompano-P, WTR	17 b	10 b	4 h	25 c	7 e
TSP-N, no WTR	127 ab	86 ab	43 bc	211 a	72 bcd
TSP-P, no WTR	79 ab	59 ab	42 bcd	158 ab	73 bcd
TSP-N, WTR	21 ab	16 ab	9 gh	39 c	19 e
TSP-P, WTR	24 ab	25 ab	14 fgh	42 c	18 e

‡Means (n = 3) of treatments during the same sampling period follow by the same letter are not different at 5% significant level by Tukey test.

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BIOGRAPHICAL SKETCH

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