Agronomic Impact of Water Treatment Residual Co-applied with Phosphorus Sources to Florida Sands

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ABSTRACT

Aluminum-rich water treatment residuals (WTR) are being suggested as amendments to immobilize excessive P in Florida soils that sorb P poorly. One of the negative impacts of land application of WTR could be excessive P immobilization that can reduce plant available P. This study evaluated the influence of application rates of WTR and various P-sources on soil and plant available P. In a glasshouse study, bahiagrass (*Paspalum notatum* Flügge) and ryegrass (*Lolium perenne* L.) were grown sequentially in a P-deficient top soil of (Immokalee sand [sandy, siliceous, hyperthermic Arenic Alaquods]) amended with four sources of P at two application levels (N- and P-based rates) and three WTR rates (0, 1 and 2.5% oven dry basis). Soils were sampled at planting of each grass and were tested for water extractable P (WEP), iron strip P (ISP), Total recoverable P (TP), and degree of P saturation (DPS). Plant dry matter (DM) accumulation and P uptake were also determined. Soil soluble P as measured by WEP and ISP, was reduced by WTR application. Phosphorus sorption capacity of the sand was improved by more than 75% by applying 2.5% WTR, and DPS reduced below 25% threshold value suggested for Florida soil. Co-applied WTR to N-based rate treatment reduced soil soluble P at planting of each plants, but plants DM yield was not reduced below that observed at P-based rate without WTR treatment. Ryegrass DM accumulation was similar for treatments with and without WTR, but P uptake was reduced with WTR. Thus, WTR has potential to improve P sorption capacity of Florida sand and reduce P loss to the environment with little or no reduction in plant growth, but plant P uptake may be affected.

INTRODUCTION

Land application of residuals such as biosolids is supported by USEPA 40 CFR Part 503 (USEPA, 1995) and other environmental agencies worldwide as long as they are applied at agronomic rates based on crop N-requirements (N-based). The N-based application of manures and biosolids usually 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 subject to offsite migration to surface water.

Phosphorus pollution of waters is a major concern in Florida because P is the limiting nutrient for eutrophication of most freshwaters (Elliott et al., 2002). The low-P retention capacities of Florida soils coupled with the characteristic flat topography and interception of shallow ground waters by discharge system favors the eventual entry of leached P to surface water bodies. Thus, control of soluble P present in residuals and manure impacted soils is very important in Florida.

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Recent work (Brown and Sartain, 2000; O'Connor and Elliott, 2001; O'Connor et al., 2002) has shown that various WTRs can be effective soil amendments in controlling soluble P. O'Connor and Elliott (2001) co-applied an Al-treated water treatment residuals (Al-WTR) with several biosolids, fertilizer, and two manures and demonstrate complete control of P leaching through Florida sands regardless of P-source applied. Land application of WTR has reduced soil soluble P from manure (Peter and Basta 1996; Cox et al., 1997) and biosolids (Ippopolitto et al., 1999) applications.

Aside from P solubility control, other potential benefits of WTR land application are increased plant nutrient availability (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 also can also increase cation exchange capacity of coarse-textured soils (American Society of Civil Engineers et al., 1996).

Potential disadvantages of land applied Al-WTRs include excessive immobilization of plant-available soil P and Al toxicity. The high P-fixing capacity reported in soil amended with WTR (O'Connor et al., 2002; Dayton et al., 2003) is similar to Andisols (phosphate retention of 85%) and can limit crop growth (Molina et al., 1991). Heil and Barbarick (1989) noted severe P-deficiency symptoms associated with an excessive rate (25 g WTR kg^{-1}) of WTR addition to soil planted to sorghum-sudangrass [*Sorghum bicolor (*L.*)* Moench - *Sorghum* x *drummondii* (Steudel) Millsp. Chase]. Ippolito et al. (1999) decreased P concentrations in blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.] by increasing WTR rates. Rengasamy et al. (1980) 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. To enhance the environmental benefit of land applied WTR without negative agronomic impact, this study evaluated the impact of P-sources and WTR co-applied to Florida sands on plant P uptake and yield.

MATERIALS AND METHODS

Top soil (0-15 cm) of an Immokalee sand (sandy, siliceous, hyperthermic Arenic Alaquods) used for the glasshouse experiments was collected from Okechobee, FL. Four sources of P were applied and included a high water soluble-P, Boca Raton biosolids and medium water soluble-P, Pompano biosolids, which were chosen to represent spectrum of biosolids that might be land-applied. The third source, poultry manure, was obtained from Tampa Farms in Indiantown, FL. The operation is representative of large egg-laying operation. The final source was triple super phosphate (TSP), which is a typical mineral P-source applied to Florida crops. Each of the P-sources was applied at two rates (N- and P-plant requirement based), and these treatments further received WTR treatments at three rates (0, 10 and 25 g kg^{-1} oven dry basis). Thus, the study was a 4x2x3 factorial experiment with one control and arranged in RCB design with three replicates.

The bulk soil was air-dried, thoroughly mixed, sieved (<2 mm) prior to analysis. Both the soil and the amendments were analyzed for Total P, Fe, Al, Ca, and Mg by ICAP following digestion according to the EPA Method 3050A (USEPA, 1986). Oxalate extractable P, Fe, Al, Ca, and Mg were determined by ICAP after extraction at a 1: 60 solid: solution ratio, following the procedures of Schoumans (2000). Total C and N of the amendments were determined by combustion at 1010 °C using a Carlo Erba NA-1500 CNS analyzer. Reaction (pH) was determined on fresh materials (1:2 solid or soil: solution ratio). Percent solids were determined by drying materials at 105 °C (Sparks, 1996).

Weight of P-sources to provide the equivalent of 44 kg total P ha^{-1} (P-based application rate) and 179 kg plant available nitrogen (PAN) ha^{-1} (N-based waste application rate) recommended by Kidder et al. (2002), were calculated from the total P and N contents. Mineralization rates of 40% of total N in biosolids and 60% of total N in manure were assumed, based on previous experience in similar studies (O'Connor and Sarkar, 1999; O'Connor et al., 2004). The P supplied by the N-based rate treatments varied with P-sources. Since the idea of the WRT treatments was to fix the P supplied at the P-based rate treatment, twice the P applied in the P-based rates (88 kg total P ha^{-1}) was applied as TSP N-based rate treatment. All treatments, including the control, received the same amount of N as NH_4NO_3 in split applications (monthly) at planting of bahiagrass only. Potassium-magnesium sulfate ("Sul-Po-Mag": 22% S, 18% K, and 11% Mg) equivalent to 444 kg ha^{-1} (1.8 g) was added to each treatment to provide adequate and uniform S, K, and Mg..

Soil (8.5 kg) and appropriate amounts of the amendments were weighed and thoroughly mixed. Water was added to bring the mixture to field capacity, and the samples were allowed to equilibrate for one week with daily mixing. Samples of the soil were taken after equilibration (1 week) for analysis (Time zero samples)

The remaining soil were packed to a bulk density of 1.3 Mg m^{-3} into a 20-cm diameter, 21 cm deep pot (6.5 liters) and planted with bahiagrass at a depth of 3 mm and seeding rate of 7 g per pot. The soil surface of each pot was covered with moist filter paper, which was wetted and kept moist daily until seed germination. After germination the filter papers were removed and soil wetted daily and moistened to initial weight once weekly. There was non-uniform germination despite the careful nurturing described which resulted in thin plant stands in some pots and the 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. Harvest was at a height of 5 cm above the soil surface with scissors or electric clippers. Grass samples were dried to constant weight at 65 ^{o}C to determine DM. After each harvest, the pots were weighed and watered as necessary after adding the supplemented N (split applied) to return to initially determined pot weights. The pots within blocks were shifted by a position twice weekly to further reduce positioning advantage in the glasshouse.

Bahiagrass was harvested four times. After DM determination, dried material was ground in a Wiley mill with stainless steel blades to pass a 20-mesh sieve and stored in airtight polyethylene containers. Ground plant material was ashed, treated with 6N HCl, and brought to final volume with distilled water as described by Plank (1992). Phosphorus in the diluted digests was determined colorimetrically (Murphy and Riley, 1962). The plant uptake (kg P ha^{-1}) was obtained as the product of P concentration and dry matter weights. Weighted means of the plant P concentrations were obtained by dividing the total P uptake by the total dry matter weight.

After the final bahiagrass harvest, soil samples were taken from the center of each pot using an auger of 5-cm diameter, and the hole created filled with time zero soil preserved for that purpose. Each pot was then planted with ryegrass (3 g seed pot^{-1}), a cool season grass, to evaluate the residual effects of the amendments. Thus, no further P-source was applied and soil obtained after the final bahiagrass harvest served as time zero soil for the ryegrass cropping.

Ryegrass was harvested three times (approximately monthly) and crop management was the same as for bahiagrass except that treatments were applied only during planting of bahiagrass. The time zero soil samples for each grass and at each harvest date of the ryegrass were all analyzed for pH and electrical conductivity (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 determined in the soils included Mehlich-1 P, WEP and ISP.

Water extractable P was determined by shaking the soil samples with deionized water at a ratio of 1: 10 soil: solution ratio for one hour (Sharpley with Moyer, 2000). The P concentration in the extract was analyzed by colorimetry using the Murphy and Riley method (1962). Mehlich 1-P (M 1-P) was determined on the samples by shaking of the soil samples for 5 min with 0.0125 M H_2SO_4 in 0.05 M HCl solution at a ratio of 1:4 soil:solution ratio (Hanlon et al., 1997). Extractants were filtered through Whatman N^o 42 filter paper and analyzed colorimetrically with the Murphy and Riley method (1962). The Iron-strip P was determined by reacting the soil samples with Fe-impregnated (0.65 M $FeCl_3$ in 0.6 M HCl) filter paper and then extracted the P adsorbed with 0.1 M H_2SO_4 (Van der Zee, 1987). The extractable P was analyzed colorimetrically with the Murphy and Riley method (1962).

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 from a source other than normal calibration 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 (duplicates). Analyses that did not satisfy the QA/QC protocol were rerun.

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. Analysis of Variance (ANOVA) was performed on DM yield, P concentrations, and P uptake of bahiagrass and ryegrass, and also on varying soil P measured in samples taken at planting of each grass using PROC GLM (SAS Institute, 1999). The data were analyzed without control treatment 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, 1, and 2.5 %) 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. The plants data and soil TP and ISP are involved in WTR-P-source rate interaction. Thus, to compare the P-source and WTR rate combinations and the control, the 7 treatments (N-based + 0% WTR, N-based + 1% WTR, N-based + 2.5% WTR, P-based + 0% WTR, P-based + 1% WTR, P-based + 2.5% WTR, and control) were reanalyzed 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 were separated by either single degree of freedom contrast procedures or Tukey method. All statistical analysis tests were done using a significance level of 5%.

RESULTS AND DISCUSSIONS

Soil and Amendments Properties

The native soil (Table 1) has low extractable P (M-1P, WEP and ISP). Soil M-1P of <10 mg kg^{-1} is considered very low for agronomic crops including bahiagrass (Kidder et al., 2002). The low P status made the soil suitable for the phosphorus response experiment, and for testing impacts of different P-sources and WTR application rates. Plant response to the 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).

Table 1. Selected properties of Immokalee soil used.

Parameters	Value
pH	5.5
Electrical conductivity, us cm^{-1}	323
C, g kg^{-1}	12.0 ±0.1†
Mehlich 1-P, mg kg^{-1}	6.40 ±0.35
Water extractable P, 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}	88.0 ±4.0
Total Fe, mg kg^{-1}	107 ±20
Total Ca, mg kg^{-1}	449 ±8
Total Mg, mg kg^{-1}	36.0 ±3.0
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

† Means of three samples ± standard deviation.

All organic sources of P used had pH of ~7.6 (Table 2); whereas the Al-WTR is acidic (pH of 5.6) and dominated by Al (157 g kg^{-1}), more than 90% (145 g kg^{-1}) of which is amorphous (0.2M ammonium oxalate extractable; McKeague et al., 1971). Total P and N were greatest in Boca Raton biosolids and least in poultry manure. Total and Oxalate Al and Fe were lower in manure than in the two biosolids, but Ca concentration in the manure was greater than in the biosolids. The greater Ca in manure could be due to the Ca-rich additives common to poultry feed, a large part of which end up in the manure. The greater oxalate P (P_{ox}) and smaller Oxalate Fe (Fe_{ox}) and Al (Al_{ox}) resulted in greater P saturation index (PSI) of Boca Raton biosolids (1.44) than in Pompano biosolids (0.7). The PSI>1 indicates excess P beyond the materials P retention capacity and agrees with the greater water soluble P in Boca Raton biosolids than in Pompano biosolids.

Table 2. Selected chemical properties of P-sources and Al water treatment residual (Al-WTR) used.

Properties	P-Source				Al-WTR
	Chicken Manure	Boca Raton Biosolids	Pompano Biosolids	TSP‡	
pH	7.7	7.6	7.6	5.9	5.5
C, g kg^{-1}	32.0	34.7	36.6	-	19.9
N, g kg^{-1}	27.0 ± 0.3†	50.4 ± 0.4†	43.1 ± 0.6†	-	0.7
Solids, %	25.1 ± 0.1†	13.4 ± 0.0†	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	-
Total P, g kg^{-1}	25.3 ± 0.3†	47.3 ± 2.3†	26.2 ± 0.2†	209	4.6 ± 0.7†
Total Al, g kg^{-1}	0.90 ± 0.10†	9.30 ± 0.40†	9.20 ± 0.40†	10.0	157 ± 3†
Total Fe, g kg^{-1}	1.50 ± 0.10†	24.3 ± 0.8†	32.8 ± 0.4†	15.7	6.0 ± 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}	5.80 ± 0.20†	10.0 ± 0.5†	4.10 ± 0.10†	6.2	0.40 ± 0.02†
Oxalate Ca, g kg^{-1}	0.04 ± 0.00†	0.06 ± 0.0†	0.05 ± 0.0†	-	0.33 ± 0.01†
Oxalate Mg, g kg^{-1}	4.20 ± 0.10†	9.70 ± 0.00†	3.70 ± 0.20†	-	0.36 ± 0.01†
Oxalate P, g kg^{-1}	12.7 ± 0.0†	34.0 ± 0.9†	20.4 ± 0.1†	186	4.3 ± 0.0†
Oxalate Fe, g kg^{-1}	0.70 ± 0.00†	19.4 ± 0.5†	24.7 ± 0.2†	11.0	5.1 ± 0.0†
Oxalate Al, g kg^{-1}	0.20 ± 0.00†	8.90 ± 0.60†	9.20 ± 0.00†	6.9	145 ± 0.4†
PSI¶	-	1.44 ± 0.02†	0.70 ± 0.02†	-	0.02 ± 0.0†

†Means of three samples ± standard deviation.
‡ Triple super phosphate.
§Water extractable P.
¶Phosphorus Saturation Index = [(0.2M oxalate P, in moles) / (oxalate Fe, in moles + oxalate Al, in moles)].

Table 3. Effects of P-source, source rate, and water treatment residuals (WTR) rate on water extractable P, mg kg^{-1} of soil sampled at planting of bahiagrass.

Source	WTR rate / Contrasts	-------------Rate----------- N-based	P-based	Contrast N- vs P-based
Manure	0 %	18.9†	6.57	*
	1 %	11.5	3.76	*
	2.5 %	5.99	2.95	*
	Linear effect	*	*	
	Quadratic effect	*	*	
Boca Raton biosolids	0 %	41.5	6.74	*
	1 %	20.9	4.02	*
	2.5 %	15.5	2.86	*
	Linear effect	*	*	
	Quadratic effect	*	*	
Pompano biosolids	0 %	6.58	4.16	*
	1 %	3.99	2.81	NS
	2.5 %	2.86	2.19	NS
	Linear effect	*	NS	
	Quadratic effect	*	NS	
TSP‡	0 %	19.6	12.4	*
	1 %	8.65	3.90	*
	2.5 %	4.12	2.18	NS
	Linear effect	*	*	
	Quadratic effect	*	*	
Contrast at 0% WTR	Manure vs Biosolids	*	NS	
	Organic vs Mineral source	*	*	
	Boca Raton vs Pompano	*	*	
Contrast at 1% WTR	Manure vs Biosolids	*	NS	
	Organic vs Mineral source	*	NS	
	Boca Raton vs Pompano	*	NS	
Contrast at 2.5% WTR	Manure vs Biosolids	*	NS	
	Organic vs Mineral source	*	NS	
	Boca Raton vs Pompano	*	NS	

† Means of three samples.
‡ Triple super phosphate.
* Significant at p = 0.05; NS = not significant.

Soil Phosphorus

The soil samples taken at planting of bahiagrass and ryegrass show WEP was affected by the sources of P, P-source rate, and WTR rates (Table 3 and 4). At bahiagrass planting, soil WEP values were greater at N-based than at P-based rate regardless of WTR rate for the manure and Boca Raton biosolids treatments (Table 3). However, similar WEP values were observed for both the N- and P-based rate of Pompano biosolids treatment at 1% and 2.5% WTR, and at 2.5% when treated with TSP. The similar WEP values probably resulted from the reduced water soluble P nature of the pompano biosolids in addition to sorption by WTR. The greater solubility of TSP makes the P assessable to sorption; hence, applying WTR at 2.5% resulted in similar WEP values of the two application rates of TSP treatment (Table 3).

Table 4. Effects of P-source, source rate, and water treatment residuals (WTR) rate on water extractable P, mg kg^{-1} of soil sampled at planting of ryegrass.

Source	WTR rate / Contrasts	Rate		Contrast
		N-based	P-based	N- vs P-based
Manure	0 %	11.5[†]	8.47	*
	1 %	5.08	2.23	*
	2.5 %	3.37	1.90	NS
	Linear effect	*	*	
	Quadratic effect	*	*	
Boca Raton biosolids	0 %	21.7	4.43	*
	1 %	6.51	1.43	*
	2.5 %	3.65	1.17	*
	Linear effect	*	NS	
	Quadratic effect	*	*	
Pompano biosolids	0 %	9.04	5.14	*
	1 %	6.67	1.40	*
	2.5 %	3.88	1.26	*
	Linear effect	*	*	
	Quadratic effect	NS	*	
TSP[‡]	0 %	11.4	8.61	*
	1 %	4.45	4.60	NS
	2.5 %	4.19	4.67	NS
	Linear effect	*	*	
	Quadratic effect	*	*	
Contrast at 0% WTR	Manure vs Biosolids	*	*	
	Organic vs Mineral source	*	*	
	Boca Raton vs Pompano	*	*	
Contrast at 1% WTR	Manure vs Biosolids	NS	NS	
	Organic vs Mineral source	NS	*	
	Boca Raton vs Pompano	NS	NS	
Contrast at 2.5% WTR	Manure vs Biosolids	NS	NS	
	Organic vs Mineral source	NS	*	
	Boca Raton vs Pompano	NS	NS	

[†]Means of three samples.
[‡]Triple super phosphate
*Significant at $p = 0.05$; NS = not significant

In general, increasing WTR rate reduced WEP regardless of P-source or P-source application rate as shown by the observed linear and quadratic effects of the WTR rates (Table 3). The only exception to this was Pompano biosolids treatments, which exhibited similar soil WEP values at different WTR rates for the P-based rate treatment. When WTR was not applied, soil WEP values differed for the different P-sources with TSP > the organic sources treatments, and Boca Raton biosolids > Pompano biosolids treatments. The trend reflects the solubility of the P-sources. However, similar WEP values were observed for the different sources when WTR was applied, indicating P-source solubility was masked by WTR applications. For the N-based rate treatment, soil WEP values differed with biosolids > manure treatments, Boca Raton biosolids > Pompano biosolids treatments, and TSP >organic source treated soils at each levels of WTR.

The WEP values of soils sampled at planting of ryegrass differed in trend from the time zero WEP values (at planting of bahiagrass). When the ryegrass was planted, WEP in manure-amended soils was similar for the two rate treatments (N- and P-based) at 2.5% WTR (Table 4). In contrast, for the P-based rate treatment of the Boca Raton biosolid, sorption of P by the WTR resulted in similar WEP values regardless of WTR rate, both of which were lower than when no WTR was applied. For the N-based rate treatment, variation in solubility of the different P-sources was masked by WTR and resulted in the similar WEP values observed for the different P-sources. In the absence of WTR, WEP values for Boca Raton biosolids-treated soils remained greater than manure- and Pompano biosolids-treated soils at planting of ryegrass. Also for the P-based rate treatment, organic-source-treated soils had lower WEP values than TSP-treated soils which could result from less mineralization of the organic P-sources than assumed. Another change observed in the trends of WEP values with time was in Pompano biosolids treatment at the P-based rate. In contrast to what was found at planting of bahiagrass, as at when ryegrass was planted, WEP was lower for the Pompano biosolids WTR treatments than untreated at P-based rate.

In general, soil WEP was lower for P-based than N-based rate treatments and lower in presence, than absence of WTR. The effect of the sources only exists when the sources were applied at N-based rate without WTR at planting of ryegrass. In the presence of WTR, similar WEP values were observed for N-based rate treatment.

The M-1P values of soil sampled at planting of bahiagrass did not differ due to WTR rates for the P-based rate treatment (Table 5). The similar soil M-1P values for the P-based rate treatment were due to the solubilizing effect of the acidic extractant on the sorbed P (Table 5). However, because of the differences in the initial P load of the two rates, M-1P was greater at N-based rate than at P-based rate at each of the three levels of WTR.

Table 5. Effects of application rates of P-sources and water treatment residuals (WTR) rate on Mehlich-1P, mg kg^{-1} of soil sampled at planting of Bahiagrass.

WTR rates and their Polynomial effect	Rate		Contrast
	N-based	P-based	N- vs P-based
0 %	85.2†	19.9	*
1 %	79.6	23.3	*
2.5 %	80.8	28.3	*
Linear	*	NS	
Quadratic	NS	NS	

†Means of twelve samples.
*Significant at p= 0.05; NS - not significant.

Table 6. Effects of P-sources and application rates on Mehlich-1P, mg kg^{-1} of soil sampled at planting of bahiagrass and ryegrass.

Time of sampling	Sources of P and their contrasts	Rate		Contrast
		N-based	P-based	N- vs P-based
At bahiagrass planting	Manure	67.4†	23.1	*
	Boca Raton	153	26.8	*
	Pompano	65.3	21.3	*
	TSP‡	41.9	24.2	*
	Manure vs. Biosolids	*	NS	
	Organic vs Mineral source	*	NS	
	Boca Raton vs. Pompano	NS	NS	
At ryegrass planting	Manure	67.0	16.1	*
	Boca Raton	73.4	14.6	*
	Pompano	50.2	12.9	*
	TSP	17.7	12.5	*
	Manure vs. Biosolids	*	NS	
	Organic vs Mineral source	*	NS	
	Boca Raton vs. Pompano	*	NS	

†Means of three samples.
‡Triple super phosphate
*Significant at p = 0.05; NS = not significant

Greater soil M-1P for the N-based rate than the P-based rate treatment was observed at planting of the two grasses irrespective of the sources of P applied (Table 6). For the P-based rate treatment, M-1P values also were similar regardless of sources because similar amounts of added P with that rate. However, the M-1 P values were variable for the N-based rate treatment due to different concentration of P in the different P-sources. The P added as the N-based rate for TSP (88 kg ha^{-1}) was smaller than the P loads from other sources (280 kg ha^{-1} from Manure, 370 kg ha^{-1} from Boca Raton biosolids and 233 kg ha^{-1} from Pompano biosolids).

Effects of the P-rate and WTR combinations along with control treatment on soil bioavailable P (as measured by ISP), and P loads (as measured by total recoverable P) are summarized in Fig. 1. Soil ISP is a measure of bioavailable P, reportedly estimating the total amount of P available for plant uptake within a growing season (Van Noordwijk et al., 1990, Koopmans et al., 2004). Across P-source, both time zero soil (planting of bahiagrass) and soil samples taken at planting of ryegrass show similar trends in the soil ISP values with WTR rate. Similar to the WEP, the ISP values were reduced with increasing WTR rates (Fig. 1a) and established the capability of WTR to reduce soil soluble P and hence P loss. At 2.5% WTR rates, the ISP of N-based rate treatment was greater than at P-based rate treatment without WTR. This implies the hazard of excess soluble P associated with N-based rate treatment could be reduced by applying WTR and at 2.5% WTR applied to N-based rate, the P assessable by the plants **is** still greater than at P-based treatment without WTR. Though the soluble P and bioavailable P measures (WEP and ISP) were reduced with WTR, the increased total recoverable P with WTR (Fig. 1b) established that

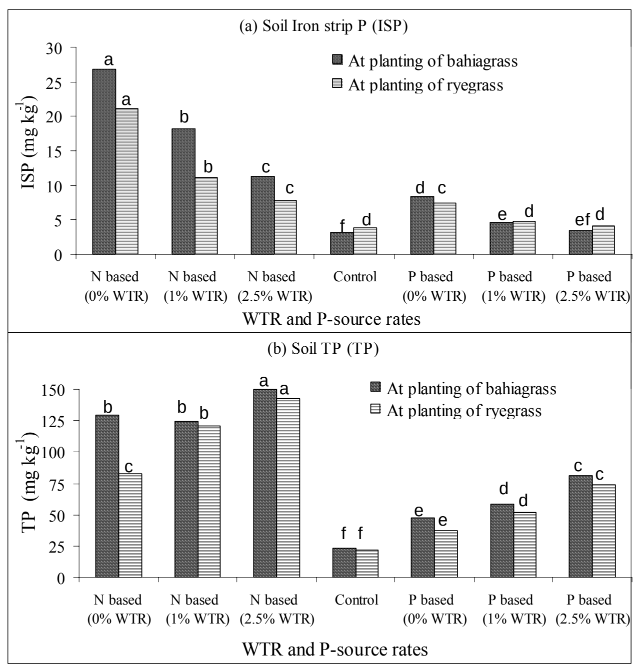

Figure 1. Effects of water treatment residual (WTR) rates and P-source rates on (a) iron strip P (ISP) and (b) Total recoverable P (TP) of soil sampled at planting of bahiagrass and ryegrass. Control treatment received neither P-source nor WTR. (Treatments within the same sampling period with same letter are not different at p-value of 0.05 by Tukey test)

Table 7. Effects of P-source and water treatment residual (WTR) rates on degree of P saturation (DPS) of soil sampled at planting of bahiagrass and ryegrass. (All DPS values are in %).

Time of sampling	Sources of P and their contrasts	WTR Rate			Polynomial effect	
		0%	1%	2.5%	Linear	Quadratic
At bahiagrass planting	Manure	103†	33.6	16.0	*	*
	Boca Raton	110	47.5	20.3	*	*
	Pompano	65.4	29.7	16.0	*	*
	TSP‡	96.3	22.9	14.5	*	*
	Manure vs. Biosolids	*	NS	NS		
	Organic vs Mineral source	*	NS	NS		
	Boca Raton vs. Pompano	*	NS	NS		
At ryegrass planting	Manure	65.7	41.7	17.5	*	*
	Boca Raton	47.2	47.6	25.7	*	*
	Pompano	60.1	32.8	18.4	*	*
	TSP	23.3	21.0	13.0	*	*
	Manure vs Biosolids	NS	NS	NS		
	Organic vs Mineral source	*	*	NS		
	Boca Raton vs Pompano	*	NS	NS		

†Means of three samples.
‡Triple super phosphate
*Significant at $p = 0.05$; NS = not significant

significant sorbed P is retained in the soil by the added WTR.

Soil Degree of Phosphorus Saturation

The degree of phosphorus saturation (DPS), is a measure of how saturated the soil is with P, and hence is an index of soil capability to hold and prevent losses of P through runoff and leaching. Soils with large DPS values suggest limited ability to retain P. The soil DPS is calculated as percentage of ratio of the soil 0.2 M oxalate extractable P to the corresponding 0.2 M oxalate extractable Fe and Al and assuming an α value of 0.55 for Florida soils (Nair et al., 2004) as:

$$DPS (\%) = [(P_{ox}) / \alpha (Al_{ox}+Fe_{ox})]*100$$

where P_{ox}, Al_{ox}, and Fe_{ox} are 0.2M ammonium oxalate extractable P, Al and Fe; all expressed as mmoles.

The DPS values of most soils amended with WTR were reduced below the threshold value of ~ 25% (Fig. 2) recommended for Florida soils (Nair et al., 2004). This is consistent with the soil soluble P measures (WEP and ISP), which were also reduced by the added WTR. Thus, addition of WTR not only reduces the excess P hazards associated with N-based rates, but also improves sorption capacity of low sorbing Florida soils.

The effect of P-source and WTR rate on soil DPS values at planting of bahiagrass and ryegrass are shown in Table 7. At planting of bahiagrass and in the absence of WTR, soil DPS values differed due to P-source; however, with the application of 1 or 2.5% WTR, the effect of the sources was removed and DPS values were similar for the different P-sources. By the time ryegrass was planted, the DPS values of mineral source treatment was further reduced at 1%WTR and differed from those observed in organic source amended soil. However, 2.5% WTR masked the effect of P-sources on DPS throughout the two plantings.

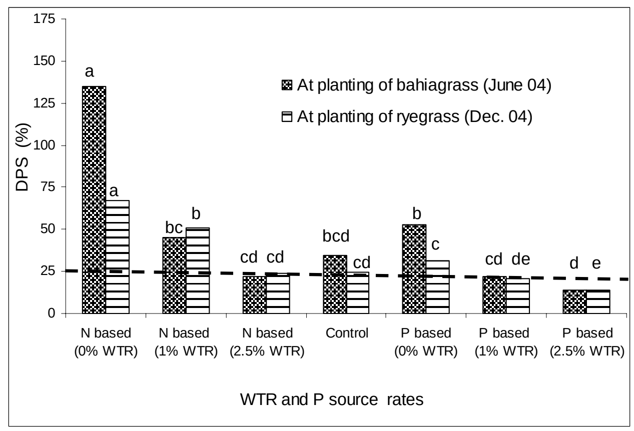

Figure 2. Degree of phosphorous saturation (DPS) values of soils samples taken at time zero (planting of bahiagrass) and at planting of ryegrass at the three water treatment residual (WTR) rate and N-based or P-based rate treatments. (Treatments within the same sampling period with same letter are not different at *p*-value of 0.05 by Tukey test).

Effect of treatments on plants

The reductions of soil WEP and ISP values with addition of WTR reflected in the plant P uptake. The P uptake was reduced with WTR across both N- and P-based rate treatments regardless of P-source applied (Fig. 3). However, the degree of reduction was dependent upon soil P pool as indicated by higher P uptake of the ryegrass for N-based rate treatment with WTR compared to the P uptake observed at P-based rate treatment without WTR. The P-based rate without WTR has adequate nutrients and expected to give optimum plant P.

As soil ISP value is expected to measure bioavailable P (Van Noordwijk et al., 1990, Koopmans et al., 2004), bahiagrass P uptake at each P-source rates and WTR were compared with the ISP values (Table 8). The P uptake by bahiagrass was less than the amount of ISP extracted from the time zero soil for the N-based rate treatment, but greater than the ISP of P-based rate treatment and the control (Table 8). Apparently for the P-based rate

Table 8. Water extractable P (WEP) and iron strip P (ISP) of soil sampled at planting of bahiagrass and P taken up by bahiagrass (on soil weight basis) for different rates of P-source and water treatment residual (WTR).

P Rate Treatment	WTR rate, %	Bahiagrass P taken up	WEP	ISP	Change in Total P†
		---------- P, mg kg^{-1} of soil ----------			
Control‡	-	5.49	3.11	3.20	1.52†
N-based	0	20.0	21.6	26.8	46.8
	1	7.77	11.3	18.2	3.92
	2.5	6.78	7.12	11.3	8.00
P-based	0	11.0	7.48	8.42	9.92
	1	5.34	3.62	4.64	6.89
	2.5	4.56	2.54	3.45	7.09

† Calculated as: Time zero Total P, mg P kg^{-1} – Soil Total P, mg P kg^{-1} after bahiagrass harvest
‡ Treatment without any P-source or WTR applied

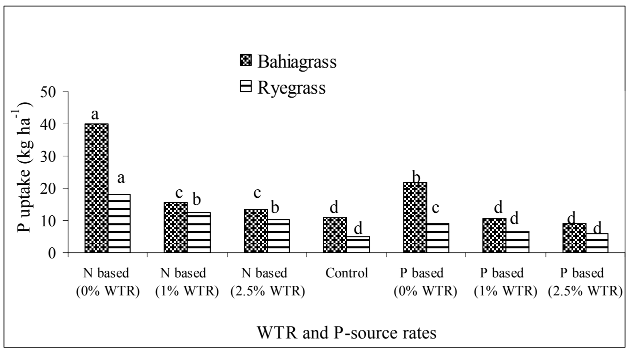

Figure 3. Bahiagrass and ryegrass P uptakes at the three rates of water treatment residual (WTR) and N-based or P-based rate treatments. (Phosphorus uptakes of same plant with same letter are not different at *p*-value of 0.05 by Tukey test).

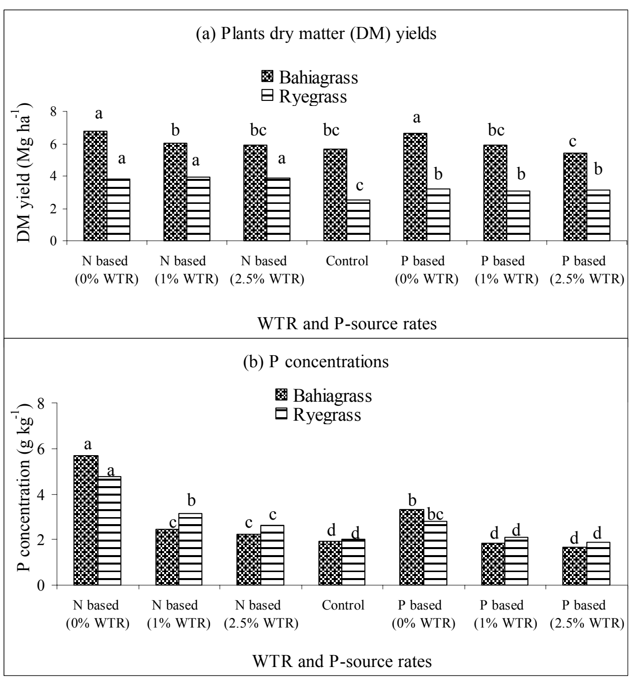

Figure 4. Bahiagrass and ryegrass (a) dry matter (DM) yields and (b) P concentrations at the three rates of water treatment residual (WTR) and N-based or P-based rate treatments. (Yields or P concentrations of same plant with same letter are not different at *p*-value of 0.05 by Tukey test).

treatment, the plant was able to remove P from sorbed P pool; however, with sufficient P accessible to the plant at N-based rate treatment, the sorbed P was not affected by the uptake. Thus the plant was able to access WTR-sorbed P in a situation with insufficient readily available soil P. Change in soil Total recoverable P for N-based rate treatment without WTR was greater than the observed plant P uptake (46.8 vs. 20 mg P kg^{-1} of soil), which could not be explained. However, at other WTR rates, the Total recoverable P change was similar to the observed plant P uptake (Table 8).

The DM yield of bahiagrass was affected by the WTR treatments (0% WTR > 1% WTR = 2.5% WTR), however ryegrass DM yield was not affected, even at 2.5% WTR. (Fig. 4a). Although the reduction in bahiagrass DM yield may have partly been associated with problems during bahiagrass establishment, reduced bahiagrass DM yield at 2.5% WTR agrees with reduced yield due to P-defficiency reported by Heil and Babarick (1989) in sorghum-sudangrass at 2.5% WTR. The P concentration of both grasses were reduced when WTR was applied (Fig. 4b), and agrees with other studies that shows plants grown in potting media treated with WTR had lower P concentrations (Bugbee and Frink, 1985; Elliott and Singer 1988; Ippolito et al., 1999

Bahiagrass and ryegrass yields were affected by P-sources and their rate as shown on Table 9. For the bahiagrass, there was no difference in yield obtained from organic- and mineral-P-sources treatments at the N-based rate due to sufficient plant available P from all the P-sources. For the P-based rate treatment, the DM yield of bahiagrass was greater from organic P-sources than mineral P-sources, but organic vs. mineral source did not affect ryegrass DM yield. Dry matter yield of both grasses fertilized with the Boca Raton biosolids were greater than in Pompano biosolids treatments for the N-based rate treatment due to greater water soluble P and hence plant available P. However, the DM yields of the two biosolids treatments were similar for P-based rate treatment. The DM yield of ryegrass in manure treatments was greater than biosolids for the P-base rate treatment, but was similar for the N-based rate treatment.

Bahiagrass DM yield was greater at N-based rate treatment than P-based rate treatment for all P-sources, except in manure amended soil. Ryegrass yield was also greater at N-based than P-based rate treatments for all P-

Table 9. Effects of P-sources and application rates on dry matter yields, Mg ha^{-1} of bahiagrass and ryegrass.

Plant	Sources of P and their contrasts	Rate		Contrast N- vs. P-based
		N-based	P-based	
Bahiagrass	Manure	4.55†	6.52	*
	Boca Raton	7.53	5.97	*
	Pompano	6.65	5.91	*
	TSP‡	6.11	5.62	*
	Manure vs. Biosolids	*	NS	
	Organic vs Mineral source	NS	*	
	Boca Raton vs. Pompano	*	NS	
Ryegrass	Manure	4.38	3.36	*
	Boca Raton	4.06	2.95	*
	Pompano	3.75	3.06	*
	TSP	3.30	3.14	NS
	Manure vs. Biosolids	NS	*	
	Organic vs Mineral source	*	NS	
	Boca Raton vs. Pompano	*	NS	

†Means of three samples.
‡Triple super phosphate
*Significant at p = 0.05; NS = not significant

sources except in TSP treated soil where similar yields were observed for the two rates possibly due to sufficient readily available P at the two rates in TSP treatments.

SUMMARY AND CONCLUSION

With good management, land application of WTR holds potential as a BMP to reduce environmental hazard associated with excess soil P in Florida sands with minimal negative agronomic impact. Phosphorus source and application rate of WTR affected soil water soluble P and ISP values, and this variation could be exploited to arrive at rates with minimal negative impact on the plants. Ryegrass DM yield was not affected by any of the WTR rate tested, but the DM yield of bahiagrass was reduced at the 2.5% WTR.

The P sorption of the sandy Florida soil was improved when WTR was applied. The reduction in soil DPS values was >75% at 1% WTR and higher than that at 2.5% WTR. Reduction of DPS values of soils treated at N-based rate ranged from around 25% to >100% , which shows the ability of WTR to lower the environmental P hazard associated with a N-based rate to below that observed at P-based rate treatment.

This study suggests that potential environmental hazard associated with N-based rate application of P-sources (biosolids, manure and mineral P-sources) can be reduced by use of WTR without measurable negative agronomic impact. As much as 2.5% WTR could be applied with a N-based rate treatment to some crops but less than 1% WTR is advised regardless of treatment rate (N- or P-based) unless higher rates are tested with a specific crop. Applying WTR to P-based rate treatment could reduce plant P concentration, but not below 1g kg^{-1} expected for pasture grass. Field study is recommended to validate the effectiveness of the residual to reduce P-loss at the recommended WTR rate.

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