Evaluating Soil Tests to Predict Bermudagrass Growth in Drinking Water Treatment Residuals with Phosphorus Fertilizer

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ABSTRACT

Drinking water treatment residuals (WTRs) may serve as a soil substitute to revegetate disturbed land. This study evaluated the use of WTRs as a soil substitute and the ability of soil tests to predict P adequacy. We measured properties and nutrient content of three WTRs (Wister, Mohawk, and ABJ) and a control soil. Bermudagrass [*Cynodon dactylon* (L.) Pers. var. Greenfield] was grown with four P treatments (0, 50, 100, and 200 mg P kg^{-1}). We measured available P by water, Mehlich 3 (M3P), and Olsen P soil extraction. Mean cumulative bermudagrass yields, across P treatments, were soil (20.6 g), Mohawk (23.6 g) > Wister (9.6 g) > ABJ (1.1 g). Tissue P concentrations were below adequate for WTR and available P in WTR was deficient for Wister and ABJ. Fertilizer P addition did not increase yield or tissue P of bermudagrass grown on WTR. However, bermudagrass grown on soil had increased yield and tissue P with fertilizer addition. The available P measured by soil tests was adequate for Mohawk and inadequate for ABJ, Wister, and soil. Although the M3P and Olsen P soil tests predicted P responses on some WTRs, with fertilizer addition, there was not a yield or tissue response. Water soluble P or Olsen P provide information on the ability of the WTR to support growth but not the ability to predict P adequacy. The M3P soil test overestimated plant availability of P in WTR due to the dissolution of P adsorbed by amorphous Al. Water extracts were the best predictor of P adequacy in WTR and should be used to determine P fertilizer additions to WTR.

DRINKING water treatment residuals are a by-product of surface water coagulation and flocculation processes in drinking water production. Drinking water treatment facilities are faced with disposal of increasing amounts of WTR produced by increased potable water production (U.S. Bureau of the Census, 1996). Prior to the early 1980s, WTRs were discharged into nearby surface waters, but currently WTRs are disposed of in landfills or on-site storage (USEPA, 1996). Increased landfill charges, federal limits on the amounts of WTR allowed into surface waters, and limited on-site storage have encouraged water treatment facilities to seek alternative disposal options (Butkus et al., 1998; Elliott et al., 1990) such as beneficial land application or as a soil substitute for reclamation projects. Beneficial land application options include using WTR to reduce dissolved P loss in runoff water from agricultural land (Basta and Storm, 1997; Coale et al., 1994; Gallimore et al., 1999; Peters and Basta, 1996) and co-application with biosolids to reduce P availability (Ippolito et al., 1999).

Dewatered WTRs have physical and chemical characteristics similar to fine-textured soils (DeWolfe, 1993) with levels of macro and micro plant nutrients comparable with soil (Elliott and Dempsey, 1991), and WTRs have been proposed for use as a soil substitute in land reclamation (USEPA, 1996). Surface mining and urban construction result in land disturbances that create a large demand for topsoil. The Office of Surface Mining reported that 16 000 ha of abandoned mine land (AML) were reclaimed in the USA during 1997 (Office of Surface Mining, 1997). Urban construction develops 400 000 ha of land yearly (USDA, 1997). The result is a need for 150 billion Mg of topsoil or soil substitute, assuming 25% of the disturbed areas require an additional 0.15 m of soil.

The primary concern with the use of WTR as a soil substitute is the potential for induced plant P deficiencies due to the high levels of amorphous Al or Fe oxides. Soil and potting media amended with alum-based WTR (0.2 to 66% v/v) increased soil structure and water holding capacity but induced P deficiencies in marigold (*Tagetes erecta* L. cv. lemondrop), lettuce (*Lactuca sativa* L. cv. iceberg), and corn (*Zea mays* L.) (Rengasamy et al., 1980; Bugbee and Frink, 1985). Application of a ferric-based WTR at 20 to 100 g WTR kg^{-1} to an Elkton silt loam (fine-silty, mixed, active, mesic Typic Endoaquult) induced P deficiency in tomato (*Lycopersicon esculentum* var. *esculentum*) (Elliott and Singer, 1988). Increasing WTR additions from 5 to 25 g WTR kg^{-1} on both calcareous (pH = 7.5) and acidic (pH = 5.2) soil significantly reduced P tissue concentrations in sorghum–sudangrass [*Sorghum bicolor* (L.) Moench 'NB280S'-*Sorghum drummondii* (Nees ex Steud.) Millsp. & Chase Stapf] (Heil and Barbarick, 1989). Cox et al. (1997) demonstrated that surface application (4.5–17.8 g dry WTR kg^{-1}) of WTR slurry (2% solids) to an acidic soil (pH = 4.4) reduced dry matter yields, tissue P concentrations, and P uptake of wheat (*Triticum aestivum* L. cv. Atlas 66). Phosphorus fertilizer addition of up to 75 mg P kg^{-1} increased yields of sorghum–sudangrass and wheat grown on WTR but did not completely eliminate tissue P deficiency (Cox et al., 1997; Heil and Barbarick, 1989). In general, these studies demonstrate that WTR application >10 g WTR kg^{-1} (20 Mg ha^{-1}) resulted in reduced tissue P concentrations but did not induce other nutrient deficiencies or toxicities.

Water treatment residuals may serve as a soil substitute in circumstances requiring minimal or nonoptimal vegetative growth, such as abandoned mine land reclamation, road corridor revegetation, or urban construction. However, the high P fixing capacity of WTR, which is similar to Andisols, which also contain large quantities of amorphous Al and Fe oxides from their volcanic origin (MacFarlane and Walmsley, 1977; Molina et al.,

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Abbreviations: ICP, inductively coupled plasma–atomic emission spectroscopy; M3P, Mehlich 3 soil test; WTR, water treatment residual.

1991), may limit the ability of WTR to support vegetation. Correcting P deficiency in WTR by adding P fertilizer may be difficult to predict. Soil extractants commonly used for determining P fertilizer requirements in soil, such as Bray I and Mehlich 3, often overestimate the plant-available P in soils with high amorphous oxide content (Gardiner and Christensen, 1991; Sanchez and Salinas, 1981). The ability of these soil extractants to measure phytoavailable P in WTR and the ability of WTR to support vegetative growth has not been determined.

The primary objectives of this experiment were to determine the ability of WTR to serve as a soil substitute and support vegetative growth and whether P fertilizer additions to WTR can eliminate P deficiency. A secondary objective was to evaluate the ability of soil tests used to measure available P to predict P adequacy of WTR.

MATERIALS AND METHODS

Properties and Nutrients of Water Treatment Residuals and Soil

We collected three alum-based WTRs from AB Jewell (ABJ), Mohawk, and Lake Wister water treatment facilities in eastern Oklahoma. Dewatering of WTR at the ABJ and Mohawk treatment plants was accomplished by ionic polymer additions and the use of belt presses. A Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustoll) was included in the study as a control soil.

Nutrient content and properties important to vegetative growth were determined for air-dried WTR and soil. We extracted readily available P with deionized water (1:5 soil to deionized H_2O; Kuo, 1996) and we extracted available P according to the M3P procedure (Mehlich, 1984) and by the Olsen P soil test (Kuo, 1996). Phosphorus in water and Olsen P extracts was determined by the modified ascorbic acid method (Kuo, 1996) while P, K, Ca, and Mg extracted by Mehlich 3 were analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP). Readily available N (NO_3-N + NH_4-N) was determined by 2 *M* KCl extraction followed by automated flow injection analysis (Mulvaney, 1996). Plant-available SO_4 was extracted using 500 mg P L^{-1} solution as $Ca(H_2PO_4)_2$ (Fox et al., 1964) and ICP analysis. We determined plant- available Fe and Zn with DTPA–TEA extraction (Lindsay and Norvell, 1978) and analysis by ICP. The pH was measured using a glass electrode, and electrical conductivity (EC) was measured in 1:2 soil to deionized H_2O extracts (McLean, 1982; Rhoades, 1996). We determined total C and N using a Carlo-Erba (Milan, Italy) NA 1500 dry combustion analyzer (Schepers et al., 1989). The cation exchange capacity (CEC) was determined by sodium saturation (Rhoades, 1982). The acid ammonium oxalate method was used to determine the concentration of noncrystalline and poorly crystalline Al forms (Al-Ox) (Ross and Wang, 1993).

Phosphorus sorption isotherms were generated by batch equilibration using 6 g soil or WTR and 150 mL of 0, 4, 8, 16, or 32 mg P L^{-1} solution. The batch equilibration conditions used were a modification of the Fox and Kamprath (1970) method.

Bermudagrass Bioassay

We performed a bermudagrass bioassay to evaluate WTR as a soil substitute and the ability of P fertilizer treatments to prevent P deficiency. Bermudagrass is a warm season grass that is often used for revegetation in the southern plains of the USA. Yield and tissue P concentration of bermudagrass, grown on three WTRs and a control soil, were evaluated with a factorial arrangement of treatments in a complete randomized design with four P treatments (0, 50, 100, and 200 mg P kg^{-1}) (SAS Institute, 1988; Steele et al., 1997). Phosphorus fertilizer was KH_2PO_4. Nitrogen was applied as NH_4NO_3 before establishment of vegetation (25 mg N kg^{-1}) and after each harvest to ensure adequate N (25 mg N kg^{-1} $harvest^{-1}$).

Bermudagrass seedlings were transplanted (5 g pot^{-1}) into 500 g of washed sand and fertilized with a P-deficient Hoagland's solution (Jones, 1997). After 3 wk, the plants were transferred to pots containing 3 kg of WTR or soil (Stanford and DeMent, 1957). Bermudagrass was grown in a controlled environment growth chamber with 16 h of daylight at 22°C for 4 mo. Moisture in the pots was maintained by adjusting to field capacity and determined gravimetrically (Peters, 1965) on a weekly basis. Bermudagrass was harvested at 36, 70, 110, and 140 days after establishment (DAE), oven-dried at 60°C for 24 h, and weighed to determine vegetative yields. Harvested tissue was wet digested using nitric and perchloric acid (Jones and Case, 1990) and the digestate was analyzed for P, K, Ca, Mg, Al, Cu, Fe, and Zn using ICP.

RESULTS AND DISCUSSION

Properties and Nutrients in Water Treatment Residuals and Soil

Bermudagrass growth of >5 Mg biomass ha^{-1} provides coverage of the soil surface and is adequate erosion control. Plant-available N soil concentration of >60 mg kg^{-1} is necessary to produce 5 Mg biomass ha^{-1} in Oklahoma (Johnson et al., 1997). Mohawk and ABJ had sufficient available N (NO_3-N + NH_4-N) while Wister and the soil were N deficient (Table 1). Only Mohawk had adequate available P measured by M3P, Olsen P, and water soluble (H_2O-P) soil tests (Table 1). Wister, ABJ, and the soil were deficient in available P and may exhibit plant deficiencies, but have the potential to respond to P fertilization. In general, plant-available indices for K, Ca, Mg, S, Fe, and Zn in WTR were sufficient for forage grasses (Brady and Weil, 1996). The pH of WTR was similar to typical soils. The electrical conductivity <4 levels of WTR were below levels that may impede growth of vegetation sensitive to salt vegetation (Zhang, 1998). All WTRs had substantial cation exchange capacity and the ability to retain cationic nutrients. Some of the WTR cation exchange capacity may be attributed to the addition of cationic flocculent in the drinking water treatment process. The organic carbon (OC) of WTR may include contributions from source water sediment, activated carbon used to remove odor and taste, and polymeric coagulants and flocculents. The ABJ and Mohawk WTRs had organic C contents much higher than typical soil. The corresponding high total N of these materials suggests C and N (Table 1) enrichment of ABJ and Mohawk by algae or other biological materials in source water. The water-extractable Al levels in WTR (in parentheses) of ABJ (0.24 mg L^{-1}), Mohawk (0.13 mg L^{-1}), and Wister (0.16 mg L^{-1}) should not inhibit root or shoot growth (Bohn et al., 1985). Aluminum solubility in WTR is similar to soil and controlled by pH (Ahmed et al., 1998). Aluminum phytotoxicity was not observed in grass grown on soil treated

Table 1. Nutrients and properties of water treatment residual (WTR) and soil materials.

		Material				
		Grant soil†	ABJ	Mohawk	Wister	Adequate range‡
Available nutrients						
NO_3–N	mg kg^{-1}	18	19	140	14	>60
NH_4–N	mg kg^{-1}	19	70	130	26	
M3P	mg kg^{-1}	7.0	8.3	39.3	20.5	>32
Olsen P	mg kg^{-1}	4.2	3.9	59.4	7.1	>12§
H_2O-P	µg L^{-1}	12.5	23.8	53.9	8.8	50–250¶
K	mg kg^{-1}	208	214	197	73.7	>125
Ca	mg kg^{-1}	1100	4640	45 800	1250	>375
Mg	mg kg^{-1}	285	73.5	121	143	>50
S	mg kg^{-1}	13.0	12.5	122	165	>3
Fe	mg kg^{-1}	16.7	7.6	58.8	89.8	>4.5
Zn	mg kg^{-1}	2.10	0.55	1.30	4.00	>0.3
Properties						Typical range for soils#
pH		6.10	7.90	7.70	6.30	5.0–8.0††
EC	dS m^{-1}	0.08	0.62	0.54	0.44	<4.00
CEC	cmol kg^{-1}	13.5	54.7	29.7	16.4	3.5–35.6
C	g kg^{-1}	5.8	77.9	155	22.2	<30
N	g kg^{-1}	0.7	10.6	14.6	2.8	0.2–5
Al-Ox‡‡	g kg^{-1}	2.5	57	26	12	3.8–7.7§§

† Fine-silty, mixed, superactive, thermic Udic Argiustoll.

‡ Nutrient requirements for bermudagrass, 5 Mg ha^{-1} or 95% sufficiency (Zhang et al., 1998).

§ Tisdale et al., 1993.

¶ Fohse et al., 1988.

Brady and Weil, 1996.

†† Bohn et al., 1985.

‡‡ Amorphous Al oxide.

§§ Range for Oklahoma soils (Dayton, 1999).

with WTR that had pH > 6. In fact, WTR additions to acidic soil increased soil pH and decreased dissolved Al (Ahmed et al., 1998).

Vegetation Yield and Response to Phosphorus Fertilizer

Bermudagrass yield for the 0 mg P kg^{-1} treatment was Mohawk > soil > Wister > ABJ (Fig. 1). Bermudagrass tissue P concentrations were below adequate for all materials. Available P in WTR was below adequate for all materials except Mohawk (Table 3). Despite WTR adequate levels of available Mg, bermudagrass tissue Mg concentrations were below adequate. Available K was adequate for ABJ and Mohawk but tissue concentrations were below adequate. Calcium, Cu, Fe, Zn, and Mn tissue concentrations were above adequate levels for all materials.

Phosphorus fertilizer was added to WTR to determine if P deficiencies could be corrected, resulting in increased yield and tissue P. Analysis of variance showed that fertilizer addition did not increase yield or tissue P of bermudagrass grown on WTR ($P < 0.05$). However, bermudagrass grown on the soil exhibited increases in yield and tissue P with fertilizer addition. Fertilizer P increased soil test P and tissue P levels from deficient to adequate and corresponded with increases in yield in soil. Despite increases in available P (Olsen and M3P) from deficient to adequate levels, fertilizer additions to Wister did not increase yield or tissue P. This suggests that Olsen P and M3P soil tests may not applicable for

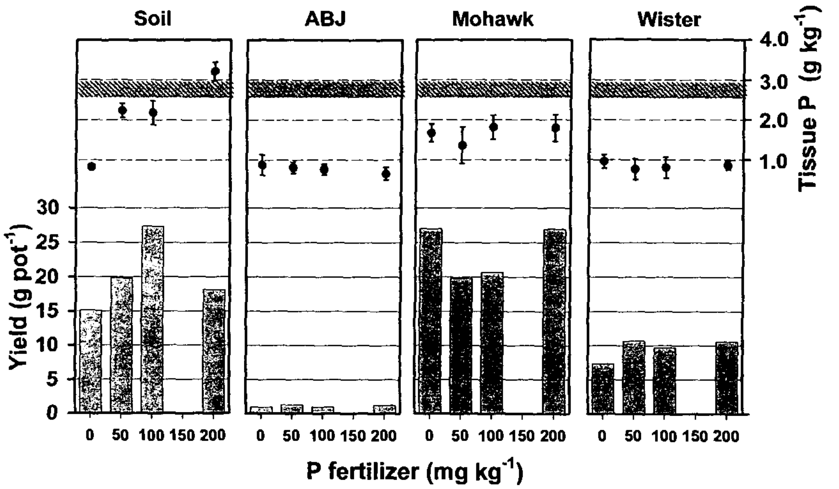

Fig. 1. Cumulative yield and tissue P concentration of bermudagrass vs. P fertilizer added to soil or water treatment residual (WTR). Adequate tissue P concentration range is indicated by the shaded horizontal bar. Error bars represent ±1 standard deviation.

Table 2. Bermudagrass tissue nutrient content from the 0 mg P kg^{-1} treatment.

	Growth media†					
	Grant soil‡	ABJ	Mohawk	Wister	Adequate for grasses	Toxic metal content
			mg kg^{-1}			
P	1 360a	324b	2 120c	1 330a	2 400–2 800§	
K	22 100a	7 300b	11 800c	23 500a	15 000–18 000§	
Ca	4 950a	5 420a	9 360b	5 990a	5 000–30 000§	
Mg	2 060ab	750c	1 350a	2 240b	3 000–10 000§	
Cu	11.1a	4.75b	12.1a	10.4a	5–20¶	100–800#
Fe	167a	423b	165a	119a	50–300¶	500–1 000#
Mn	142a	727b	180a	347c	10–50¶	400–1 000#
Zn	47.0a	29.2a	33.9a	40.7a	15–30¶	300–500#
Cd	0.43	0.71	0.14	0.43		<1

† Mean values with the same letter are not significantly different ($P < 0.05$) than values in the same row.
‡ Fine-silty, mixed, superactive, thermic Udic Argiustoll.
§ Kelling and Matocha (1990).
¶ Marschner (1995).
# Toxic range for livestock (National Research Council, 1980).

WTR or that another variable is inhibiting growth. Lack of yield response to P fertilizer on Mohawk is consistent because it contained sufficient levels of available P. Very deficient available P levels in ABJ are consistent with poor yield and fertilizer additions may be too small to produce a tissue P response. Analysis of variance showed that cumulative bermudagrass yield across P treatments (mean in parentheses) were soil (20.6 g), Mohawk (23.6 g) > Wister (9.59 g) > ABJ (1.11 g) at $P < 0.05$ (Fig. 1). Tissue P (mean in parentheses) followed a similar trend of soil (2.1 g kg^{-1}) > Mohawk (1.7 g kg^{-1}) > Wister (0.85 g kg^{-1}) > ABJ (0.78 g kg^{-1}).

Bermudagrass Trace Metal Content

Bermudagrass tissue concentrations of Cd, Cu, Fe, Mn, and Zn were all below the ranges reported to be toxic to livestock by the National Research Council (1980) (Table 2). In general, bermudagrass trace metal accumulation for WTR was not higher than plants grown on the soil. Similar findings have been reported in other studies where uptake of Cd, Cu, Fe, or Zn by tomatoes, loblolly pine (*Pinus taeda* L.), sorghum–sudan, or wheat grown on mixtures of WTR and soil up to 600 g WTR kg^{-1} soil were not increased (Bugbee and Frink, 1985; Cox et al., 1997; Elliott and Singer, 1988; Geertsema et al., 1994; Heil and Barbarick, 1989).

Table 3. Available P in water treatment residual (WTR) and soil treated with P fertilizer.

		Available P		
Material	P addition	Water	Olsen	M3P
	mg kg^{-1}	µg L^{-1}	mg kg^{-1}	
ABJ	0	23.8	3.9	8.3
	50	11.1	5.7	8.1
	100	10.0	5.3	13.7
	200	11.3	5.8	25.7
Mohawk	0	53.9	59.4	39.3
	50	57.5	60.8	46.2
	100	43.3	73.8	46.8
	200	54.2	83.0	50.2
Wister	0	8.8	7.1	20.5
	50	10.4	13.6	32.4
	100	11.7	20.9	44.6
	200	20.8	29.9	66.7
Soil	0	12.5	4.17	7.0
	50	97.8	16.2	35.0
	100	203	30.1	42.4
	200	2600	82.0	104
	Adequate	50–250†	12‡	32§

† Fohse et al., 1988.
‡ Tisdale et al., 1993.
§ Brady and Weil, 1996.

Measurement of Available Phosphorus in Water Treatment Residuals by Soil Tests

We evaluated the ability of three soil-extracting solutions (Mehlich 3, Olsen, water) to measure available P and determine the ability of WTR to support vegetative growth. The Mehlich 3 soil test is widely used by soil testing laboratories to measure plant-available P, K, and Mg and make fertilizer recommendations (Fixen and Grove, 1990). The Olsen P soil test is recommended for measuring available P in calcareous soils.

The available P measured by all soil tests was adequate for Mohawk and inadequate for ABJ, Wister, and soil. The P extracted by M3P and Olsen soil tests of the unamended WTR followed the same trend as the bermudagrass yield of Mohawk > Wister > ABJ (Table 3, Fig. 1). Fertilizer P resulted in a linear increase in M3P for Wister ($r^2 = 0.99$), ABJ ($r^2 = 0.92$), soil ($r^2 = 0.97$), and Mohawk ($r^2 = 0.82$, $P < 0.10$). Fertilizer additions increased M3P to adequate soil test P levels and should have resulted in increases in yield and tissue P for Wister, ABJ, and soil. With the exception of ABJ ($r^2 = 0.53$), Olsen-extractable P increased linearly with P fertilizer addition for Wister ($r^2 = 0.99$), soil ($r^2 = 0.97$), and Mohawk ($r^2 = 0.99$). The Olsen soil test showed increased extractable P with P fertilizer addition to supposedly adequate levels in Wister and soil and should have resulted in increases in yield and tissue P but did not. Water-extractable P increased linearly with P fertilizer addition for Wister ($r^2 = 0.93$) but did not reach adequate levels. Water-extractable P did not predict a yield or tissue P response due to fertilizer addition. Soil test P, yield, and tissue P increased with P addition to the soil. Although the M3P and Olsen P soil tests predicted P responses on some WTRs, there was no yield or tissue response to P fertilizer for bermudagrass grown on WTR.

Perhaps the strong acidity (pH ≈ 2.4) and fluoride concentration (0.015 *M* F^-) of the Mehlich 3 solution dissolved excessive amounts of P associated with amor-

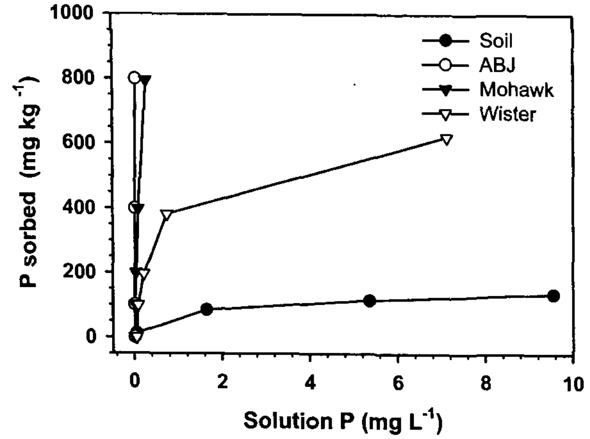

Fig. 2. Phosphorus sorption isotherms for water treatment residual (WTR) and soil.

phous Al and Fe oxides that are not plant available. Similarly, P extracted by acid solutions containing fluoride is poorly correlated to plant response on high-P-fixing Andisols (Baravalle et al., 1993; Cajuste et al., 1992; Leal et al., 1994).

Water-extractable P can be used to estimate readily available plant P (Fixen and Grove, 1990). The soil solution P concentration considered to be critical for plant response varies from 0.05 to 0.25 mg L^{-1} and depends on the plant species and the P buffering capacity of the soil (Fohse et al., 1988; Fox, 1981; Fox and Kamprath, 1970; White, 1981). Water solubility of P is strongly correlated with the Al-Ox fraction of WTR ($P < 0.01$), which suggests that low levels of water soluble P were the result of the high amount of amorphous Al in these WTR materials (Dayton, 1999). Amorphous Al contents of 12 g kg^{-1} for Wister, 26 g kg^{-1} for Mohawk, and 57 g kg^{-1} for ABJ are much larger than the amorphous Al of 2.5 g kg^{-1} for soil (Table 1). The capacity of WTR and soil to sorb P from solution followed the same trend as amorphous Al content (Fig. 2). Low solubility of P and high amorphous Al content of the WTR compared with soil suggest that WTR may produce P deficiencies in vegetation. Amorphous Al in WTR was within the range (5.1 to 60.7 g kg^{-1}) reported for Andisols in Costa Rica and Panama (Molina et al., 1991), which require massive inputs of P fertilizer to achieve P adequacy. Apparently, much larger amounts of P fertilizer addition to WTR are required to increase water-soluble P and achieve a P response.

SUMMARY AND CONCLUSIONS

Vegetative yields and tissue data indicated that Mohawk and Wister could be used as a soil substitute for land reclamation. The ABJ material is not suitable for vegetative growth due to the low P availability. However, the high P sorption characteristics of ABJ may serve as a sink for P in agricultural soils with excessive amounts of available P. Beneficial use of WTR as a soil substitute would benefit the general public by lowering municipal costs and help protect the environment by converting unproductive land into healthy ecosystems capable of supporting both plant and animal communities.

Phosphorus additions of 200 mg P kg^{-1} did not increase the plant availability of P on the WTR materials, although P additions did increase the yield and tissue P concentrations of bermudagrass grown on soil. The high P adsorption by WTR was similar to P adsorption by volcanic ash–based allophanic Andisols that require massive P to increase yields of tomatoes, potatoes (*Solanum tuberosum* L.), and corn to optimal production levels. Band application of P is recommended for crop production on Andisols and may be a useful management practice for WTR.

Soil tests based on water-soluble or Olsen P can provide information on the ability of the WTR to support growth but may not be able to predict P adequacy. However, the Mehlich 3 soil test overestimated plant availability of P in WTR due to the dissolution of amorphous Al adsorbed P. Water extracts were the best predictor of P adequacy in WTR and plant response to P fertilizer. Phosphorus fertilizer additions to WTR should be based on water-extractable P criteria.

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