

An Alum-Based Water Treatment Residual Can Reduce Extractable Phosphorus Concentrations in Three Phosphorus-Enriched Coastal Plain Soils

J. M. Novak* and D. W. Watts

ABSTRACT

The accumulation of excess soil phosphorus (P) in watersheds under intensive animal production has been linked to increases in dissolved P concentrations in rivers and streams draining these watersheds. Reductions in water dissolved P concentrations through very strong P sorption reactions may be obtainable after land application of alum-based drinking water treatment residuals (WTRs). Our objectives were to (i) evaluate the ability of an alum-based WTR to reduce Mehlich-3 phosphorus (M3P) and water-soluble phosphorus (WSP) concentrations in three P-enriched Coastal Plain soils, (ii) estimate WTR application rates necessary to lower soil M3P levels to a target 150 mg kg⁻¹ soil M3P concentration threshold level, and (iii) determine the effects on soil pH and electrical conductivity (EC). Three soils containing elevated M3P (145–371 mg kg⁻¹) and WSP (12.3–23.5 mg kg⁻¹) concentrations were laboratory incubated with between 0 and 6% WTR (w w⁻¹) for 84 d. Incorporation of WTR into the three soils caused a near linear and significant reduction in soil M3P and WSP concentrations. In two soils, 6% WTR application caused a soil M3P concentration decrease to below the soil P threshold level. An additional incubation on the third soil using higher WTR to soil treatments (10–15%) was required to reduce the mean soil M3P concentration to 178 mg kg⁻¹. After incubation, most treatments had less than a half pH unit decline and a slight increase in soil EC values suggesting a minimal impact on soil quality properties. The results showed that WTR incorporation into soils with high P concentrations caused larger relative reductions in extractable WSP than M3P concentrations. The larger relative reductions in the extractable WSP fraction suggest that WTR can be more effective at reducing potential runoff P losses than usage as an amendment to lower M3P concentrations.

CLUSTERING the livestock industry into the southeastern portion of North Carolina has seriously stressed the soils' abilities to assimilate manure nutrients (Barker and Zublena, 1995; Furuset, 2001; Cahoon and Ensign, 2004). Because land available for manure application is limited, some fields have received excessive manure applications, which have caused soils to contain several hundred kilograms of plant available P per ha (Sims et al., 1998; Novak et al., 2000; Hansen et al., 2002). These levels are several-fold higher than the P concentration range considered optimum for crop growth in sandy Coastal Plain soils (M3P concentrations between 51 and 100 mg kg⁻¹; Sims et al., 2002). Off-site P losses via runoff (Pote et al., 1996; Sharpley et al., 2000) and leaching (Novak et al., 2000) can be high from soil containing excess soil P concentrations. Phosphorus

losses from agricultural sources are recognized as a major cause of water quality impairment in many inland and coastal waters (USGS, 1999; Boesch et al., 2001).

The high incidence of nutrient-impaired water bodies in the Mid-Atlantic region has resulted in the creation of nutrient management guidelines and laws limiting over-application of manure. A few states in the Mid-Atlantic region have placed emphasis on using soil M3P concentrations as guidelines for P-based nutrient management plans. For example, in Maryland, when soil M3P concentrations exceed 150 mg kg⁻¹, a P-based site index test must be completed (Sims et al., 2002). In Delaware, when soil M3P concentrations exceed 150 mg kg⁻¹, inorganic or organic P sources applied to soils can be restricted if crop P removal is less than the P applied (Sims et al., 2002).

In the Southeastern Coastal Plain region, off-site P movement is facilitated by soils having a low ability to bind P (Harris et al., 1996; Hansen et al., 2002). These soils are less likely to retain P, and continual manure application can easily saturate particle surfaces, resulting in accelerated off-site P transport (Hansen et al., 2002). Reductions in soil extractable P concentrations (Peters and Basta, 1996; Codling et al., 2000) and off-site P transport from manure treated soils (Dayton et al., 2003) have been demonstrated by adding chemical by-products that contain Al- and Fe-oxide and hydroxides. These studies employed WTRs, a by-product produced during drinking water purification of ground and surface water sources. Drinking water treatment municipalities add alum [Al₂(SO₄)₃], poly-Al hydroxide, or a Fe-salt to raw water to settle out impurities. By adding WTRs to manure treated soils, both runoff and soil extractable P concentrations are reduced because soluble P binds with the Al- and Fe-oxide and hydroxide groups forming an insoluble complex (Peters and Basta, 1996; Elliott et al., 2002). Both Dayton et al. (2003) and Novak and Watts (2004) reported that WTRs can differ substantially in P binding maxima because of variations in their oxalate extractable Al and Fe concentrations caused by variations in purification procedures.

Water treatment residuals can contain a variety of salts as a result of the chemical purification process. For example, some drinking water treatment plants will add caustic soda (Na₂O) to neutralize pH increases from alum and/or potassium permanganate (KMnO₄) to oxidize organic compounds. There may be soil fertility and other environmental issues if these ions significantly alter basic soil quality properties like soil pH and EC. Alterations in soil pH can reduce crop nutrient availabil-

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Abbreviations: Al_{ox}, oxalate-extractable aluminum; EC, electrical conductivity; Fe_{ox}, oxalate-extractable iron; M3P, Mehlich-3 phosphorus; WSP, water-soluble phosphorus; WTR, water treatment residual.

ity and nutrient releases due to microbial mineralization, while increase in soil EC values may increase soil salinity conditions to phytotoxic levels (Sparks, 1995). Laboratory studies, however, have shown that WTRs mixed into high P soils will not severely lower soil quality properties (pH and EC) important for plant growth (Peters and Basta, 1996; Codling et al., 2000; O'Connor et al., 2002).

Laboratory studies have successfully demonstrated the ability of WTRs to reduce soil extractable P concentrations in Maryland (Codling et al., 2000) and Oklahoma (Peters and Basta, 1996). These studies incorporated different levels of WTRs into soils with high P concentrations and reported considerable reductions in extractable P. These two studies, however, did not investigate relationships between WTR application rates and extractable P concentration reductions to a target soil P threshold level. This information would be particularly germane to the water treatment industry for the alternate use of WTRs and for nutrient management agencies as a counter measure to reduce offsite P movement from soils with excess P concentrations. Our objectives were to: (i) evaluate the ability of an alum-based WTR to reduce soil M3P concentrations and water-soluble P concentrations in three P-enriched sandy soils, (ii) determine WTR amounts that must be applied to these soils to reduce their M3P content to equal the 150 mg kg⁻¹ soil threshold concentrations level, and (iii) determine potential impacts of WTR applications on basic soil quality properties (pH and EC). The soil test P threshold level chosen for this study was based on the soil concentration established in Delaware and Maryland (M3 soil test P concentration of 150 mg kg⁻¹; Sims et al., 2002).

MATERIALS AND METHODS

Collection of Soils and Water Treatment Residual

The three soils used in this study were collected from a field in Duplin County, North Carolina. The field is in permanent pasture of Coastal Bermuda grass [*Cynodon dactylon* (L.) Pers.]. It is located adjacent to a swine production facility and received intensive rates (83–625 kg P ha⁻¹ yr⁻¹) of liquid swine manure effluent for 10 yr (Novak et al., 2003, 2004). The predominate soil series in this field is an Autryville loamy sand (loamy, siliceous, subactive, thermic Arenic Paleudults), with inclusions of Lakeland sand (thermic, coated Typic Quartzipsamments). The Autryville series is a well-drained soil formed in sandy and loamy marine sediments of the North Carolina Coastal Plain physiographic region. The Lakeland soil series is an excessively drained soil formed in Aeolian sands (Daniels et al., 1999).

A previous investigation revealed that topsoil M3P concentrations were quite variable across the field (Novak et al., 2000); therefore, three sampling locations were chosen to provide a relative range of soil M3P concentrations (high, medium, and low). Topsoils (0–15 cm deep) were collected, returned to the laboratory, air-dried, and crushed to pass a 2-mm sieve.

Drinking water treatment residual was collected from a North Carolina drinking water treatment facility that treats raw water pumped from the Nuese River. This treatment plant uses alum to flocculate silt and clay-sized river sediments and

potassium permanganate to oxidize organic compounds. Additional descriptive information of raw water characteristics, facility treatment procedures, and alum application rates has been reported (Novak and Watts, 2004). The WTR was air-dried, crushed, and 2-mm sieved.

Extraction of Phosphorus

Soils and the WTR were extracted using Mehlich 3 reagent and quantified using colorimetric methods (Mehlich, 1984). In this procedure, 2.5 g of sample was extracted with 25 mL of Mehlich 3 reagent (1:10 solid to solution ratio). After centrifugation, the supernatant was filtered through 0.45- μ m filter media, and the P concentration was measured colorimetrically at 882 nm. Water-soluble P was extracted using deionized H₂O according to SERA-17 methods (Southern Extension/Research Activity, 2000). In the SERA-17 procedure, 2.5 g of sample was extracted with 25 mL of deionized H₂O (1:10 solid to solution ratio) for 1 h. The solution was treated as above, except it was acidified to pH 2 using concentrated HCl. The WSP was quantified using the colorimetric method of Murphy and Riley (1962).

Characterization of Soil and Water Treatment Residual Chemical Properties

The soils and WTR pH and EC values were determined at a 1:2 (v v⁻¹) solid to liquid ratio. Total P was extracted using a modified digestion method of Gallaher et al. (1976), where ground apple leaves were used as an internal P standard (Standard Reference Material 1515; National Institute of Standards and Technology, Gaithersburg, MD). The digested P was quantified using the ascorbic acid method (Greenberg et al., 1992). The oxalate-extractable aluminum (Al_{ox}) and iron (Fe_{ox}) contents in the WTR and soils were determined using a modified method of McKeague and Day (1993), where 25 mL of 200 mM ammonium oxalate reagent was used instead of 10 mL. The initial 0.25 g of sample per 10 mL extraction ratio was insufficient to quantify the total Fe_{ox} and Al_{ox} contents, so the ratio was increased to 0.25-g sample per 25 mL. All analyses were done in triplicate.

Incubation of Soils with Water Treatment Residual

Sufficient WTR was mixed with 25 g of soil to produce a series of WTR to soil treatments of 0, 1, 2, 4, and 6% (w w⁻¹). Six percent WTR mixed into Soil 1 (highest M3P concentration) was insufficient to lower soil M3P concentrations to the target threshold level. An additional incubation experiment was conducted on this soil using higher WTR to soil treatments (10, 12.5, and 15%). The treatments were placed into triplicate 30-mL glass centrifuge tubes and were laboratory incubated for 0 and 84 d. During the incubation, all tubes were maintained at 10% (w w⁻¹) moisture content, which represents the typical soil moisture content at field capacity for sandy topsoils in the Carolina Coastal Plain region (W.J. Busscher, personal communication, 2004). Periodically (every 2 to 3 d), the caps were removed to allow for air exchange, and sufficient water was added to account for moisture losses before resealing. The incubation mean low and high temperature and relative humidity over the 84-d period ranged between 21.1 and 22.4°C and 44.6 and 52.0%, respectively. At termination, the WTR to soil treatments were removed from the tube for soil pH and EC measurements and for extraction of M3P and WSP.

Statistics

A one-way analysis of variance was used to determine significant differences (at $P < 0.05$ level) between mean extract-

able M3P and WSP concentrations and for pH and EC value changes between the % WTR treatments after 84 d of incubation. All pair wise comparisons between mean treatment values were further tested for significant differences using the Holm–Sidak method.

The effects of WTR amendment on extractable M3P and WSP concentrations were examined by comparing these concentrations in untreated (0% WTR) samples at the beginning of the incubation (T_0) to concentrations extracted from WTR treatments ($x\%$ WTR) at 84 d (T_{84}). The relative reductions between untreated and treated soils were estimated by:

$$\% \text{ reduction} = T_0 \text{ soil P (mg kg}^{-1}\text{)}_{0\% \text{ WTR}} - T_{84} \text{ soil P (mg kg}^{-1}\text{)}_{x\% \text{ WTR}} / T_0 \text{ soil P (mg kg}^{-1}\text{)}_{0\% \text{ WTR}} \quad [1]$$

A simple linear regression analysis was used to determine if a relationship existed between either soil M3P or WSP concentrations and the % WTR (0–6%) treatments. Higher WTR to soil treatments were added to Soil 1 to determine soil M3P concentrations reductions to the target 150 mg kg⁻¹ soil P threshold level. The mean soil M3P concentrations from these higher mixtures (10, 12.5, and 15%) were merged with data from the lower mixtures of Soil 1 and an additional linear regression analyses was performed. All statistical analyses were determined using SigmaStat Version 3.0 software (SPSS, 2005).

RESULTS AND DISCUSSION

Initial Chemical Properties of Soils and Water Treatment Residual

Middle Coastal Plain topsoils in North Carolina that formed under a mixed-forest stand cover typically have acidic pH values (<5; Novak and Watts, 2004). In this field, however, repeated swine manure effluent applications have resulted in near neutral pH values (pH < 7). Swine manure effluent contains an abundance of excreted soluble salts like Ca, Mg, and K, which when added to soil, will eventually cause a pH and EC increase. In comparison with soils, the WTR has a mildly acidic pH value, and the EC value is several-fold higher (Table 1). The lower pH and higher EC value of WTR is due to the utilization of alum, oxidizers, and clarifying agents during the raw water purification process.

The reagents used in this study differ significantly in their ability to extract P from binding sites. Deionized H₂O will extract the WSP held in pore water, and loosely bound to solid and organic phases. Mehlich 3 reagent, on the other hand, is an acidic solvent that will extract the WSP fraction, as well as P bound to oxides and hydroxides (Mehlich, 1984). Phosphorus extracted from

soils with high P contents using deionized H₂O likely represents P concentrations that can be lost through runoff and/or leaching, whereas soil P concentrations measured using Mehlich 3 reagent represent that P fraction available for plant uptake. One goal of adding WTR to soils with high P contents is to reduce the amount of extractable WSP and M3P concentrations by forming insoluble P complexes with Al- and Fe-oxides and hydroxides.

All three manure-treated topsoils contain appreciable concentrations of WSP and M3P (Table 1). The soils contain between 1.5 to 7.3 times more M3P than is considered optimum for crop growth in sandy Coastal Plain soils (M3P concentrations between 51 and 100 mg kg⁻¹; Sims et al., 2002). Additionally, the mean soil M3P concentration contained in Soils 1 and 2 are between 1.6- to 2.5-fold higher than the 150 mg kg⁻¹ M3P concentration threshold level. The soils released between 12.3 to 23.5 mg kg⁻¹ of WSP. In comparison, very low topsoil concentrations of WSP (1.2 mg kg⁻¹, unpublished data) and M3P (7.5 mg kg⁻¹; Novak et al., 2000) were extracted from a nearby mixed forest-covered Autryville soil with no history of swine manure application. The several-fold increase in topsoil M3P and WSP concentrations was caused by long-term swine manure effluent applications (Novak et al., 2000).

Only small amounts (<0.1% of the total P) of WSP and M3P were extracted from the WTR (Table 1), implying very strong P binding by the WTR. Dayton et al. (2003) reported that low P extractability of WTR was due to an abundance of Al_{ox} and Fe_{ox} functional groups. The Al_{ox} and Fe_{ox} of the WTR were an order of magnitude greater than the Al_{ox} and Fe_{ox} concentrations of the soils (Table 1), which is consistent with smaller amounts of P extracted from the WTR and the soil. The larger WTR Al_{ox} and Fe_{ox} concentrations result from the large liquid alum concentrations (120–170 mg L⁻¹) employed during water purification (Novak and Watts, 2004) and the high Fe-containing mineral content of sediments originating from Piedmont soils (Daniels et al., 1999).

Reductions in Mehlich-3 Phosphorus and Water-Soluble Phosphorus

Incorporation of WTR into all three soils reduced M3P concentrations relative to untreated soils (0% WTR, Fig. 1). The magnitude of the decline varied between soils and by % WTR incorporation. Mixing between 1 and 4% WTR into Soils 1 and 2 resulted in significant M3P concentration declines relative to untreated soils, but this did not occur in Soil 3 (Fig. 1). Incorporating between 1 and 4% WTR into Soils 1 and 2 caused a relative soil M3P concentration reduction of between 17 and 50 mg kg⁻¹ compared to untreated soils. For all three soils, reductions in soil M3P concentrations were most apparent after 6% WTR incorporation because the concentrations were decreased between 37 and 112 mg kg⁻¹. Using Eq. [1], this translates to a percentage M3P decrease of 30, 40, and 26%, respectively, for Soils 1, 2, and 3.

Table 1. Initial chemical properties† and characteristics of three soils and a water treatment residual (WTR).‡

Material	pH	EC	WSP	M3P	Total P	Al _{ox}		Fe _{ox}	
						— mg kg ⁻¹ —		g kg ⁻¹	
		dS m ⁻¹							
Soil 1	6.5	0.19	23.5	371	0.50	0.73	0.48		
Soil 2	6.6	0.30	18.2	235	0.53	0.60	0.37		
Soil 3	6.7	0.28	12.3	145	0.40	0.40	0.26		
WTR	5.8	1.04	3.6	2.6	4.25	145	26		

† EC, electrical conductivity; WSP, water-soluble phosphorus; M3P, Mehlich-3 phosphorus; Al_{ox}, oxalate-extractable aluminum; Fe_{ox}, oxalate-extractable iron.

‡ Results are the means of triplicate measurements.

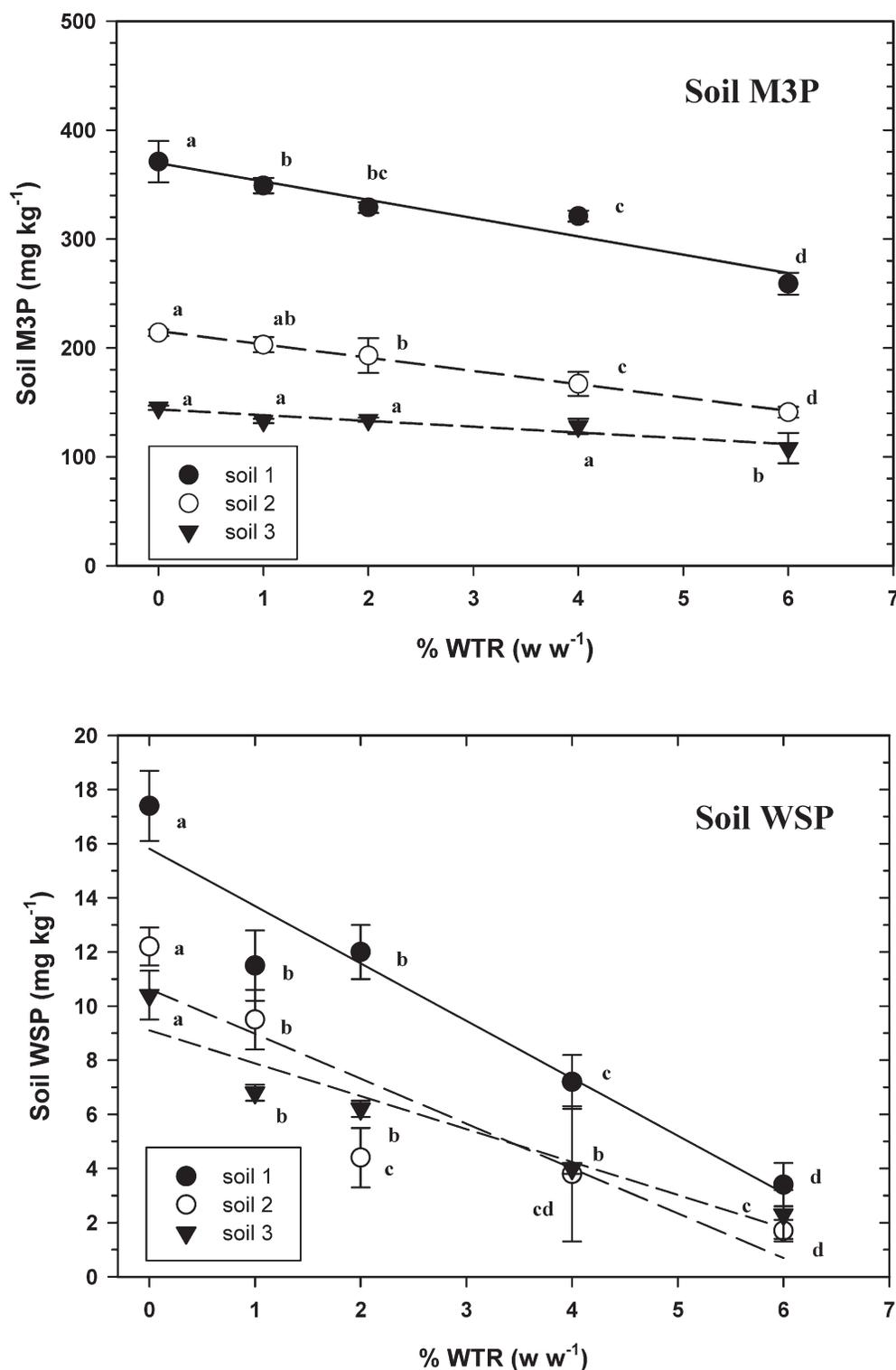


Fig. 1. Linear regression relationship between reductions in soil Mehlich-3 phosphorus (M3P) and water-soluble phosphorus (WSP) concentrations and percent water treatment residuals (WTR) incorporation. Mean values with a different letter are significantly different at $P < 0.05$.

Similarly, incorporation of WTR into these three soils reduced WSP concentrations relative to the untreated soils (Fig. 1). The magnitude of the WSP concentration decline also varied between soils and by % WTR incorporation. The initial soil WSP concentrations in untreated Soils 1, 2, and 3 were 23.5, 18.2, and 12.3 mg

kg⁻¹, respectively. After mixing in 6% WTR, the soil WSP concentrations declined to between 1.7 to 3.4 mg kg⁻¹ (Fig. 1). Using Eq. [1], incorporating between 1 and 6% WTR into the soils resulted in relative WSP concentration reductions between 45 and 91%. This means that the alum-based WTR was effective at reduc-

ing WSP concentrations in manure-treated soils. Several other researchers (Peters and Basta, 1996; Codling et al., 2000; Elliott et al., 2002) noted similar declines in WSP concentrations after residuals were mixed into manure treated soils. The magnitude of this reduction has important consequences on surface water quality because small dissolved P concentrations ($0.01 \text{ mg dissolved P L}^{-1}$; Sharpley and Rekolainen, 1997) can accelerate eutrophication. Reductions in WSP desorbed from high P soils mean potential decreases in runoff P loads transported into surface water bodies.

There was a strong linear and significant relationship between soil WSP and M3P concentrations vs. % WTR incorporation (Fig. 1 and Table 2). This is an interesting finding because an operator applying swine manure effluent can develop a relationship between a target P level reduction and WTR application. Therefore, building on the relationship shown in Fig. 1, WTR application rates necessary to reduce soil M3P concentrations to the 150 mg kg^{-1} soil M3P threshold level were determined. Using the linear regression equation for Soil 2 (Table 2), 5.3% WTR is needed to reduce soil M3P concentration from 235 to 150 mg kg^{-1} . This prediction is similar to the soil M3P concentration reduction (141 mg kg^{-1}) obtained after 6% WTR was incorporated into Soil 2. This means that an operator, to reduce the soil M3P concentration to the target threshold level, would have to apply 119 Mg ha^{-1} of WTR to this field and mix the WTR to 15 cm deep (assumes Soil 2 bulk density was 1.5 g cm^{-3}). Soil 3 had an initial mean M3P concentration that was below the threshold level. To maintain Soil 3 M3P concentration below the upper threshold, incorporation of as little as 1% WTR (22.5 Mg ha^{-1}) would predictably reduce the M3P concentration to 138 mg kg^{-1} .

Reducing the mean M3P concentration in Soil 1 to below the threshold level was more difficult compared to results obtained for Soils 2 and 3. Soil 1 had very high soil M3P concentrations (371 mg kg^{-1}) and after 84 d of incubation the 6% WTR addition had only reduced soil M3P concentrations to 259 mg kg^{-1} . The inability to reach the M3P threshold level may be due to not reaching a true equilibrium state with P binding within 84 incubation days. Previous P sorption studies with WTR have reported that P equilibrium is diffusion controlled, limited by P access into micropores (Makris et al., 2004). Additionally, organic carbon distribution and concentration associated with WTR is also a rate-limiting sorption factor by influencing P diffusion toward the interior of the residual (Makris et al., 2004).

The inability to reduce Soil 1 M3P concentration by 221 mg kg^{-1} (371 mg kg^{-1} minus 150) suggested that additional quantities of WTR beyond 6% were needed. To arrive at an estimate, the regression equation for Soil 1 (Table 2) was extrapolated to predicate that 12.6% WTR should supply sufficient binding sites to fix 221 mg kg^{-1} of soil M3P. To verify this estimation, an auxiliary experiment was conducted by mixing higher WTR levels into Soil 1 (10, 12.5, and 15%). The tubes were incubated and extracted using the same procedures as the initial WTR mixtures. The results demonstrated that mixing

Table 2. Simple linear regression relationships between reduction in soil Mehlich-3 phosphorus (M3P) and water-soluble phosphorus (WSP) concentrations and percent water treatment residual (WTR) incorporation (using 0–6% WTR treatments).

Soil	Regression equation	r^2	P
M3P			
1	$y = 369 - 16.8x$	0.928	0.008
2	$y = 215 - 12.2x$	0.998	<0.001
3	$y = 143 - 5.3x$	0.896	0.015
WSP			
1	$y = 15.8 - 2.1x$	0.932	0.008
2	$y = 10.6 - 1.6x$	0.838	0.029
3	$y = 9.1 - 1.2x$	0.910	0.012

in the additional WTR did reduce the M3P concentrations in Soil 1 (Fig. 2). Mixing in 10 and 12.5% WTR, respectively, only reduced the soil M3P concentration to 216 and 197.4 mg kg^{-1} . Incorporation of 15.0% WTR into Soil 1 reduced the soil M3P concentration to 178 mg kg^{-1} , which was also insufficient to reach the upper soil M3P threshold level (shown as a dashed line in Fig. 2). This shows that our initial prediction of 12.6% WTR was underestimated. The inability of these high WTR to soil treatments to reduce M3P concentration within 84 d may simply be from error associated with the extreme extrapolation, or due to WTR inaccessibility to P held on intraparticle sites (Makris et al., 2004). It is also conceivable that more time was required for WTR to achieve true equilibrium conditions with P held within soil particles (Makris et al., 2004).

To ascertain a more accurate estimate for the % WTR required to reduce Soil 1 M3P concentration to 150 mg kg^{-1} , another linear regression relationship was calculated based on using all of the % WTR treatments with the M3P concentrations (Fig. 2, $n = 8$). The regression relationship was also near-linear ($r^2 = 0.97$) and significant ($P < 0.001$). From this regression relationship (slope = 13 and y intercept = 358), it was estimated that 16% WTR would be required to reach the threshold level in 84 d. Applying 16% WTR to a 1-ha field may be logistically difficult considering that this % WTR translates into a field application rate of 360 Mg ha^{-1} (mixed to a 15-cm depth and soil bulk density of 1.5 g cm^{-3}). This estimate was also obtained using alum-based WTR having P sorption maxima of 85 mg g^{-1} (Novak and Watts, 2004). Utilization of other WTR material that contains lower P sorption maxima could greatly raise WTR application rate estimates.

Water treatment residuals applied at 360 Mg ha^{-1} will form a 2.4-cm-thick surface layer across a field. This is a large application rate and is an impractical task because of WTR availability and transportation cost issues. Considering these constraints, it may be impractical in soils with excess P contents to fully reduce the M3P concentration to the 150 mg kg^{-1} threshold level in a short period of time (84 d). In soils containing lower M3P concentrations ($<235 \text{ mg kg}^{-1}$), WTR incorporation can be a useful chemical-based best management practice for soil M3P concentration reductions to levels near or lower than the target threshold level.

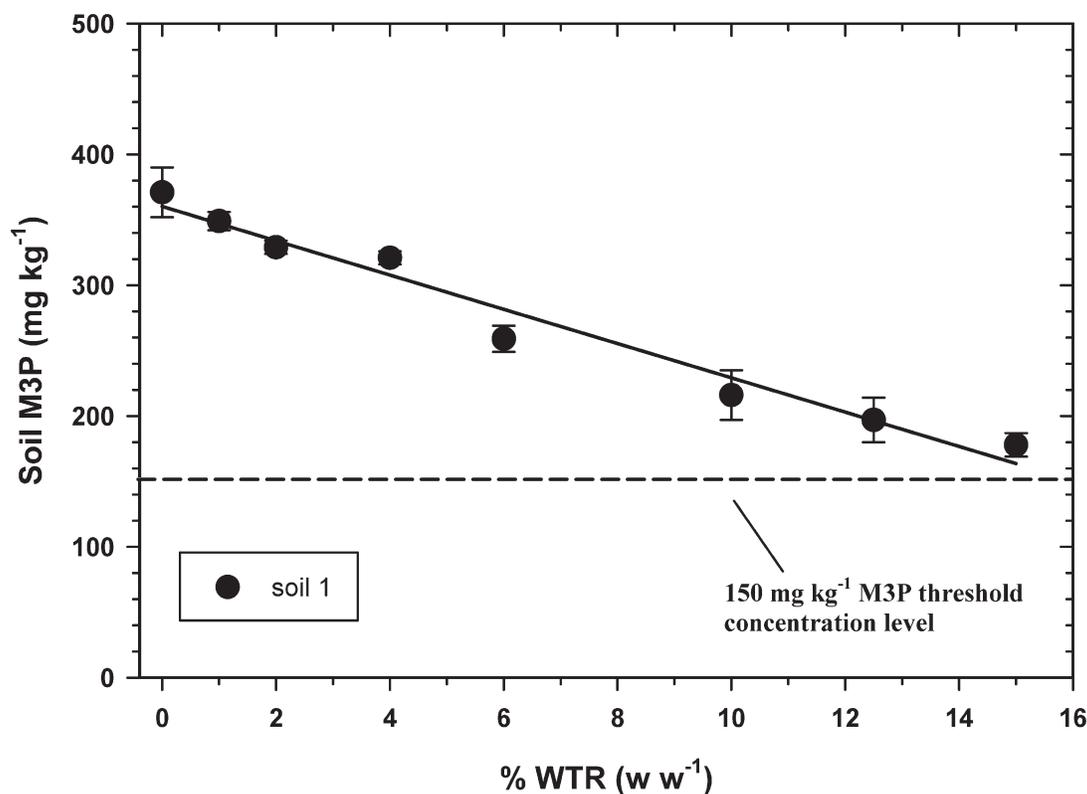


Fig. 2. Linear regression relationship between reductions in Mehlich-3 phosphorus (M3P) concentration in Soil 1 and percent water treatment residuals (WTR) (0–15% WTR) incorporation. The horizontal line represents proposed maximum soil Mehlich-3 phosphorus (M3P) concentration threshold.

Potential Soil Quality Impact

Purification of raw water for drinking purposes requires the use of a variety of chemicals. Consequently, the WTR can contain a mixture of anions and cations. Water treatment residual application to soils has raised issues about possible changes in soil pH and EC increases due to an abundance of ionic species. Soil pH and EC were determined to ensure that WTR additions (0–6%) did not cause undesirable soil quality impacts. After 84 d of incubation with WTR, there was a significant, albeit small decrease in soil pH values compared to untreated soils (<0.5 unit; Fig. 3). The soil pH decline is attributable to the release of H^+ or Al^{3+} from the WTR because it has a mildly acidic pH value (Table 1). Incorporating higher amounts of WTR (15%) into Soil 1 resulted in a significant pH decline from 6.5 to 5.72 ($P < 0.001$).

Soil EC values in Soils 1, 2, and 3 were significantly altered after 1 to 6% WTR incorporation (Fig. 4). Compared to untreated soils, mixing in 4 to 6% WTR almost doubled the soil EC to values approaching 0.6 dS m^{-1} . Incorporating the higher amounts of WTR (10–15%) into Soil 1 also caused a small, but significant increase ($P < 0.001$) in soil EC values (0.6 dS m^{-1}) compared to control (0.3 dS m^{-1}). The slight increase (<0.4 dS m^{-1}) should have a minimal impact on plant growth because corn (*Zea mays* L.) and peanut (*Arachis hypogaea* L.) are sensitive to saline conditions at soil EC values between 1.7 and 3.2 dS m^{-1} , respectively (Sparks,

1995). Additionally, the longevity of the ions in these sandy soils should be short-lived. A laboratory experiment showed a 50% reduction in Na, Mn, and S concentrations between two water leachates collected from pots containing a sandy soil with 6% WTR (unpublished data).

CONCLUSIONS

There are many literature reports documenting impaired water quality from excess soil P concentrations in fields that have received long-term manure applications. To reduce these water quality issues, a few Mid-Atlantic states have passed nutrient management laws, regulations, and guidelines that use a soil M3P concentration threshold level. If this level is exceeded, a P site index must be assessed that would either reduce off-site P transport using buffers or restrict manure application rates. Off-site P movement reductions have been obtained after applying WTRs to manure treated soils. This approach is a novel chemical-based best management practice because WSP and M3P concentrations are significantly lowered. This study confirmed that WTR incorporation into three soils with varying soil P concentrations significantly reduced extractable WSP and M3P concentrations. Reductions in WSP were relatively higher than M3P concentration declines implying that WTR may be particularly effective at lowering runoff P losses.

Increasing the WTR mixture rate caused a linear de-

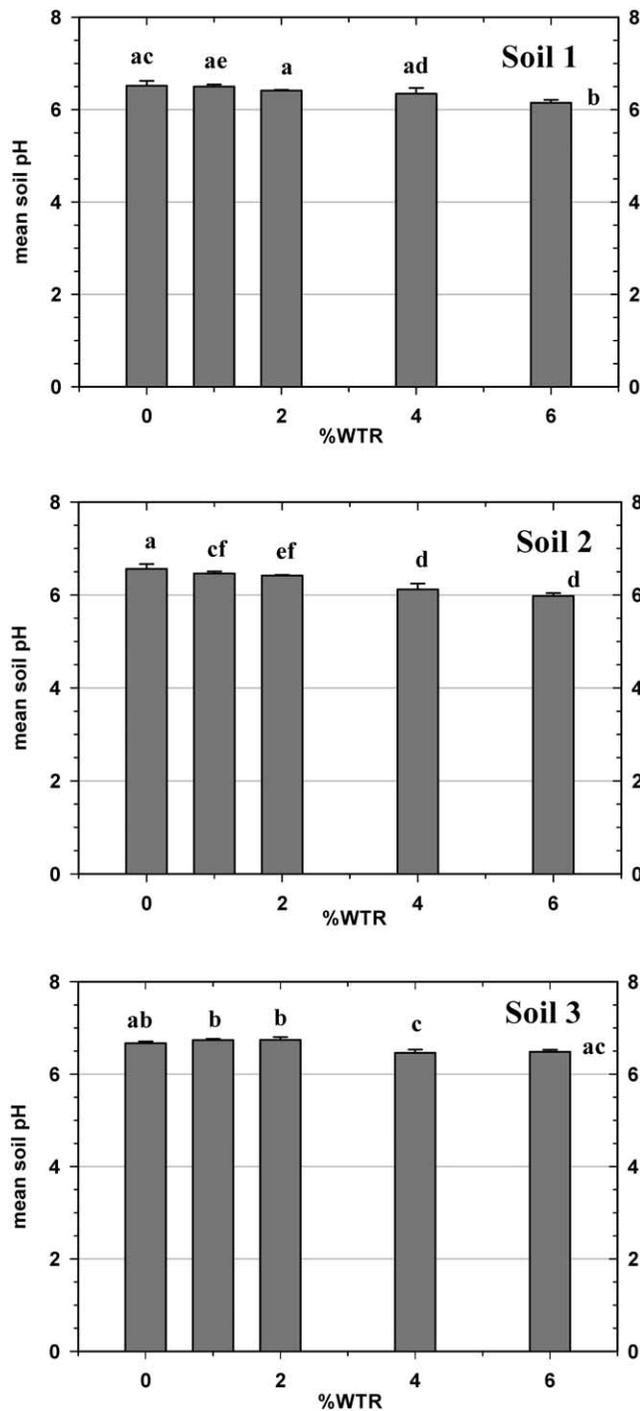


Fig. 3. Mean pH values in unamended and amended soils. Bars with a different letter are significantly different at $P < 0.05$ within each soil.

crease in the soil extractable P concentrations. This relationship was used to establish a theoretical WTR application rate needed to reduce soil M3P concentrations to a target threshold level. For two soils containing M3P concentrations between 145 and 235 mg kg⁻¹, applying 6% WTR resulted in a lowering of the soil M3P concentration to levels below the soil P threshold concentration level. This suggests that periodic WTR applications can

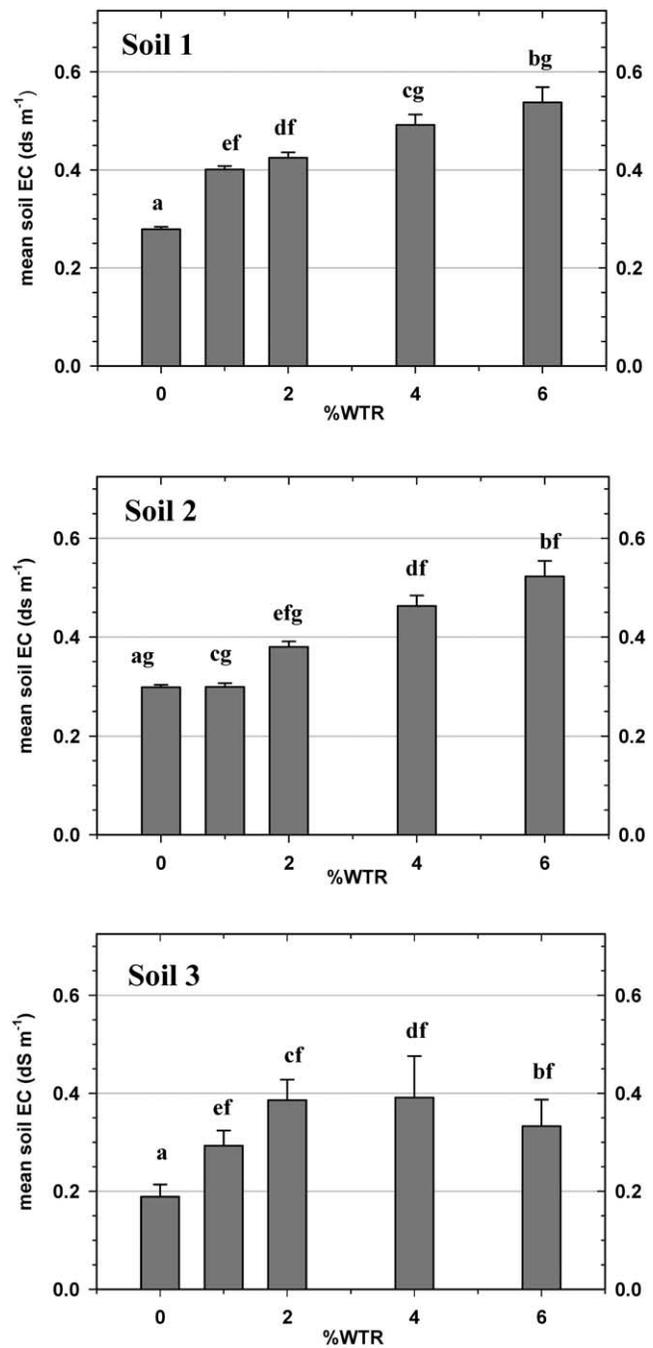


Fig. 4. Mean electrical conductivity (EC) values in unamended and amended soils. Bars with a different letter are significantly different at $P < 0.05$ within each soil.

reduce soil M3P concentrations to values close to an environmental threshold level.

Developing a best management practice that uses an alum-based WTR to reduce soil M3P concentrations may not be applicable for all manure treated soils. For soils with high M3P concentrations (>370 mg kg⁻¹), WTR application rates of several hundreds metric tons per ha were needed to reach the threshold level. Under these soil P situations, logistic challenges of applying large amounts of WTR may limit its usefulness as a P-fixing agent. Care should also be exercised when apply-

ing this large WTR amount to ensure that soil M3P concentrations are not reduced to levels below crop nutrient requirements. In this study, WTR applications were shown to have minimal adverse soil quality impacts on soil pH and EC values.

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