

Development of Indices to Predict Phosphorus Release from Wetland Soils

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The U.S. Environmental Protection Agency created the Clean Water Action Plan to develop nutrient criteria for four water body types: lakes and reservoirs, rivers and streams, estuaries, and wetlands. Significant progress has been made in open water systems. However, only areas in and around the Florida Everglades have had numeric nutrient criteria set, due to the complexity, heterogeneity, and limited information available for wetlands. Our objective was to evaluate various soil tests to predict significant P release potential of soil in wetlands. A total of 630 surface soil samples (0–10 cm) were collected for this study from four southeastern states: Florida, Alabama, Georgia, and South Carolina. Soil samples were collected from the center of wetlands, the edge of the wetlands, and from adjacent uplands. The phosphorus saturation ratios (PSR), calculated using P, Fe, and Al molar concentrations from Mehlich 1 (M1-PSR), Mehlich 3 (M3-PSR), and oxalate (Ox-PSR) extractions and the amount of P extracted by different extractants were used to predict P loss potential from a soil. Total phosphorus (TP) concentration in wetland soils, estimated as the 75th percentile of the distribution of least impacted wetland soils as an example, was approximately 550 mg kg⁻¹. Based on this reference background condition, procedures for obtaining threshold values for P release to the surrounding water bodies were developed and threshold values calculated: M1-P = 24 mg kg⁻¹, M3-P = 44 mg kg⁻¹, Ox-PSR = 0.079, M1-PSR = 0.101, and M3-PSR = 0.067.

POLLUTION from agricultural and other anthropogenic sources have been identified as the major cause of degradation of water bodies (USEPA, 1996). In 1972, the Federal Water Pollution Control Act (FWPCA) was amended by Congress to include state designation of water bodies by their uses and for states to determine standards by which water bodies would be held to protect designated use.

In 1987, the Water Quality Act (WQA), passed by the Federal government, set goals to develop and implement 'numeric' criteria for all pollutants based on water, soil, or plant parameters. The Clean Water Action Plan (CWAP) designated four categories of water bodies, lakes and reservoirs, rivers and streams, estuaries, and wetlands (USEPA, 1996) and also provided recommendations for development of numeric nutrient criteria for aggregate level III ecoregions (USEPA, 2000a, 2000b, 2001, 2007).

The concept of ecoregions was developed in the 1980s to help USEPA establish ecologically similar areas within the contiguous 48 states based on climate, geological morphology, vegetation, soil and agricultural use (McMahon et al., 2001; Omernik, 1987). Within most of the 14 ecoregions, numeric nutrient criteria for most water body types have been established. However, wetlands, with exception of ecoregion XIII (Fig. 1) still do not have recommended nutrient criteria assigned by USEPA or developed by states. Recently guidance has been provided to states in the development of numeric criteria for wetlands (USEPA, 2007). In this guidance, two principal approaches have been recommended: (i) determine the relationships between causal and response variables and thereby identify thresholds of nutrients that would impair designated use or (ii) select a value based on statistical distribution of nutrient concentration in least impacted reference wetlands within a given class and region. The reference condition approach would presume protection of ecological integrity if nutrient levels were below a particular level and presume impairment if nutrient concentrations were above a particular level. In recommending numeric values for various water bodies and ecoregions, USEPA has commonly used the 75th percentile within least-impacted populations or the 25th percentile of all members of a population (USEPA, 2000a).

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Abbreviations: DPS, degree of phosphorus saturation; M1-Al, M1-Fe, and M1-P; Mehlich 1-extractable aluminum, iron, and phosphorus; M3-Al, M3-Fe, and M3-P; Mehlich 3-extractable aluminum, iron, and phosphorus; Ox-Al, Ox-Fe, and Ox-P; oxalate-extractable aluminum, iron, and phosphorus; PSR, phosphorus saturation ratio; M1-PSR, phosphorus saturation ratio calculated as $M1-P/(M1-Fe + M1-Al)$; M3-PSR, phosphorus saturation ratio calculated as $M3-P/(M3-Fe + M3-Al)$; Ox-PSR, phosphorus saturation ratio calculated as $Ox-P/(Ox-Fe + Ox-Al)$; STP, soil test phosphorus; TP, total phosphorus; WSP, water-soluble phosphorus.

Phosphorus is one of the major nutrients that has been identified as having a direct impact on the water quality of a wetland (Bedford et al., 1999; Bollens and Ramseier, 2001; Ewel, 1976; Finlayson et al., 1986; Gusewell et al., 1998; Kadlec and Bevis, 1990; Pauli et al., 2002) and is typically the limiting nutrient for primary productivity in many freshwater systems (North American Lake Management Society, 1992). Although many of the P sorption and retention capacities of wetland soils are similar to the upland soils, there are notable differences that exist. As a result of fluctuating water levels and highly adapted vegetation that can transfer oxygen from aboveground stems and trunks to roots within anaerobic soils, numerous aerobic-anaerobic interfaces exist. These interfaces can facilitate nutrient transformations as well as restrict rates of carbon respiration and oxidant availability. Within this environment P retention is regulated by various physicochemical properties such as pH, redox potential, Fe, Al, Ca content of wetland soils, and organic matter (OM) content as well as some processes such as adsorption, ligand exchange, and precipitation (Reddy et al., 2005). It was reported that significant correlations exist between amorphous and poorly crystalline forms of Fe and Al with P retention maximum of soils (Khalid et al., 1977; Reddy et al., 1998; Richardson, 1985). This type of correlation suggests that P sorption and subsequent retention in wetlands is associated with amorphous and poorly crystalline forms of Fe and Al (Reddy et al., 2005). Although the influence of anaerobic conditions may limit the role that some sorption sites may play in soil P sorption in wetlands, extraction techniques developed for upland conditions might be extended to test for similar soil parameters and P availability in wetland soils.

In the upland ecosystem, several soil chemical extraction methods are often used to determine the availability of P and other plant available nutrients present in soil (Sims et al., 2000). These soil tests for phosphorus (STP) have been extensively evaluated and have been related to response variables such as plant bioavailability, leachability, and surface runoff (Maguire and Sims, 2002a). Recently, there have been several studies using soil tests conducted to predict the risk of P release to the surrounding water bodies by leaching or surface runoff (Sotomayor-Ramirez et al., 2004). Researchers have shown that there are highly significant correlations between STP and P in surface runoff or leachable P or simply water-soluble phosphorus (WSP) (Bundy et al., 2001; Cox and Hendricks, 2000; McDowell and Sharpley, 2001; Pautler and Sims, 2000; Sotomayor-Ramirez et al., 2004; Torrent and Delgado, 2001).

There is a growing interest to apply STP developed for upland soils to saturated and inundated soils to indicate potential thresholds of nutrient impairment in wetland systems. However, wetland soils have very different characteristics, most notably a significant higher organic matter than upland soils. Because of these differences in soil characteristics, questions regarding the usefulness and relationship between extraction methods developed for uplands and their environmental implications under flooded or wet soil conditions are poorly understood.

This study attempts to use a soil test for P or a P-related parameter, for example, PSR (Chrysostome et al., 2007a; Maguire and Sims, 2002a, 2002b; Nair and Harris, 2004; Nair et al., 2004),

which have been used in upland studies, as an indicator of potential P release from wetland soils. The objectives of this study were to (i) identify routine STP or P-related parameters that could be used as indicators of P release from the soil to the water column in wetland soils, irrespective of location or type of wetland, (ii) determine the relationship between the identified indicator and other wetland soil parameters such as OM, pH, bulk density (BD) and metal concentrations extracted by various soil extraction processes, and (iii) establish how threshold values may be assigned to the identified indicators for protection of water quality.

Materials and Methods

Location of Study Sites

Soil samples were collected from three ecoregions: Southeastern Temperate Forested Plains and Hills (IX), Southern Coastal Plain (XII), and Eastern Coastal Plain (XIV) (McMahon et al., 2001; Omernik, 1987) (Fig. 1). The samples were collected from four southeastern states: Florida (FL), Alabama (AL), Georgia (GA), and South Carolina (SC). Sampling sites in several states occurred in different ecoregions: FL (IX, XII), AL (IX), GA (IX), and SC (IX, XII, XIV). The total number of soil samples collected was 630 of which 331 were affected by anthropogenic activities (impacted) and 299 were taken from minimally-impacted sites. Impacted or minimally-impacted sites were distinguished based on surrounding land use. Minimally-impacted sites were selected within State Forests, National Forests, or other federal lands with little or no watershed disturbance. Impacted sites occurred in active agricultural areas. Wetland community types include riverine swamp, nonriverine swamp, riverine marsh, and nonriverine marsh. Site selection used a stratified random approach using data from the National Wetlands Inventory (NWI). Wetlands within desired sampling regions were vegetatively classified as swamp or marsh, then classified as riverine or nonriverine. The distinction between riverine and nonriverine wetlands was made by applying a 40-m buffer along streams identified in the National Hydrography Dataset compiled by USGS. All NWI polygons lying at least partially within the 40-m buffer were classified as riverine; all polygons not intercepted by that buffer were considered nonriverine. Only wetlands along first and second order streams were selected. This allowed for greater certainty when evaluating the degree of land use influence upstream of riparian systems. Before sampling, classification of candidate wetlands was verified and the impact condition of the wetland relative to adjacent land use was defined.

Soil Sampling and Characterization

Surface soil (0–10 cm) samples were collected from the wetland center (A), wetland edge (B), and adjacent upland (U) during 2003 and 2004 (Fig. 2). Soils were sampled using a 7-cm diameter polycarbonate core with a stainless steel cutting head; soil cores were collected to a depth >10 cm. Cores were then extruded into a 10-cm ring of similar diameter to the core and cut off at 10 cm. This provided a sample volume of 385 cm³. Soil samples were composited from three areas within the center, edge, or upland zone of the wetlands to provide representative

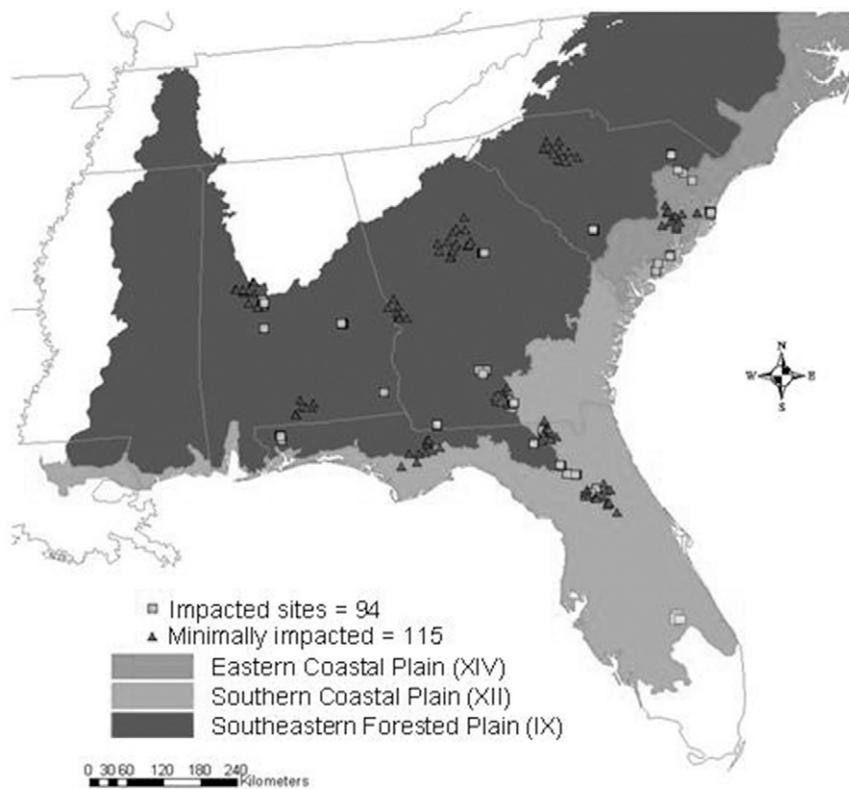


Fig. 1. Map of the locations where the soil samples were collected during the Southeastern Wetland Biogeochemical Survey study (Source: Paris, 2004).

samples for each location. The samples were thoroughly mixed and air dried before characterization. Soil pH was determined

using 1:2 soil to solution ratio on air-dried soils. Soil BD was determined by the Grossman and Reinsch (2002) procedure.

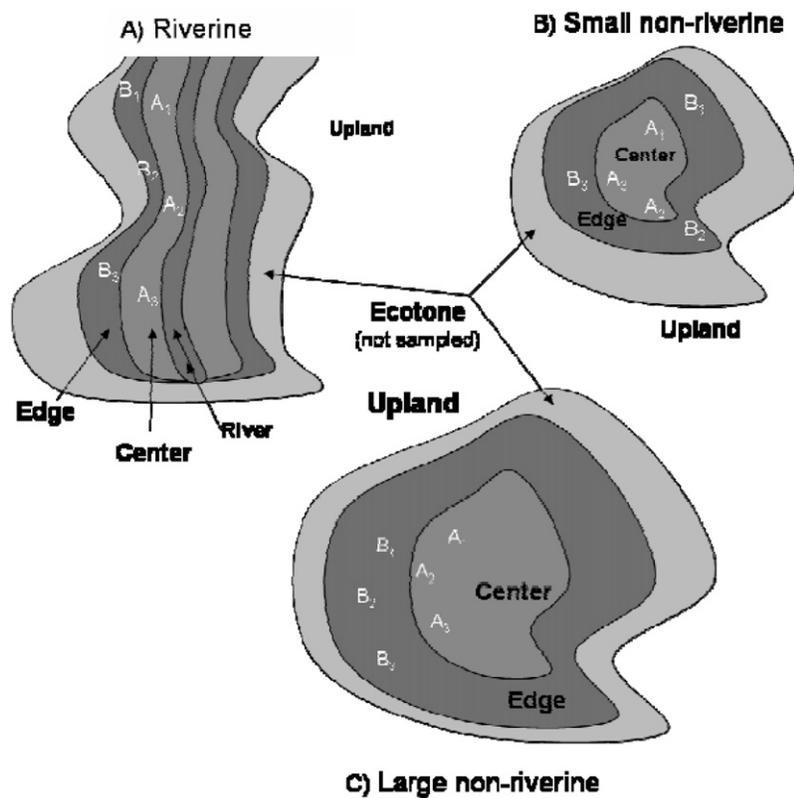


Fig. 2. Field sampling scheme adopted during the Southeastern Wetland Biogeochemical Survey study (Source: Paris, 2004).

After air drying, soils were ground to pass through a 1-mm mesh sieve. Total carbon (TC) (Nelson and Sommers, 1996) and TP (Anderson, 1976) were also determined. Soil samples were analyzed for P, Fe, and Al by Mehlich 1 (M1) (Mehlich, 1953), Mehlich 3 (M3) (Mehlich, 1984), WSP (1:10 soil/water ratio), and oxalate (Ox) (McKeague and Day, 1966) extractions. Water soluble extracts were obtained by shaking 2 g of soil with 20 mL of double deionized water, shaking for an hour, and filtering through a 0.45 μm filter paper. The solutions were analyzed for P colorimetrically by the molybdate blue method (Murphy and Riley, 1962) using a Technicon II colorimetric auto analyzer using USEPA Method 365.1 (USEPA, 1993). All other extracts for P and extractable metals Fe and Al were analyzed by inductively coupled plasma atomic emission spectroscopy, available in state soil testing laboratories for analyses of P and metals in M1, M3, and Ox solutions.

Calculation of Phosphorus Saturation Ratio

The PSR was calculated as:

$$\text{PSR} = (\text{P})/(\text{Fe} + \text{Al}) \quad [1]$$

where P, Fe, Al concentrations (expressed in moles) determined in Mehlich 1 (M1), Mehlich 3 (M3), or oxalate (Ox) extracts. Based on Eq. [1] the different PSR of wetland soils were calculated as M1-PSR, M3-PSR, and Ox-PSR.

Statistical Analyses

Simple regression analyses were run by using Excel 2003. Other regression and correlation analyses were computed with JMP version 4.0 (SAS Institute, 2000) and MINITAB version 14.0 (Minitab, 2004) software packages. Stepwise regression analyses were performed with different sets of independent variables pH, BD, OM, TC, M1-P, M3-P, Ox-P, and PSR, in various extracts (M1-PSR, M3-PSR, and Ox-PSR) to predict variability of WSP by using SAS (SAS Institute, 2001).

Results and Discussion

Extractable Soil Phosphorus for Wetland Soils

A wide range of extractable soil P was observed for each of the soil extractants used in this study (Table 1). The P concentration of the wetland soils varied as Ox-P > M3-P > M1-P > WSP which was the same trend as reported elsewhere for upland soils (Maguire and Sims, 2002a, 2002b; Nair et al., 2004). Mehlich 1-P and Mehlich 3-P were used to assess the fertility status of soils and therefore regarded as agronomic soil tests. However soil P tests such as WSP or Ox-P were developed more for environmental purposes (Maguire and Sims, 2002b; Sharpley et al., 1996; Sims and Coale, 2002; Sims et al., 2000). The linear correlation between M1 and M3 extracted P was weak for center of wetland (A) ($R^2 = 0.46$, $P < 0.0001$), moderate for edge of wetland (B) ($R^2 = 0.56$, $P < 0.0001$), and strong for adjacent uplands (U) ($R^2 = 0.81$, $P < 0.0001$) (Fig. 3), indicating that the two extractants target different P pools; this is true for A and B, not for U. Further, the simple regression coefficient (R^2) and the slope of the regression line both increased from center of wetland to the upland through edge of the wetland (Fig. 3) which

means that the P extracted by the different procedures depends on the amounts of different P forms present in soils from which the soil sample was collected. For example, M3 extracts larger amounts of Fe than M1 (Table 1) and would partly account for the variation in slopes of the M1/M3 regressions for the center of wetland, edge of wetland, and the upland (Fig. 3).

The soils in our study are carbonate free and TC is largely organic carbon (OC); the TC in our wetland soils is significantly related to OM ($R^2 = 0.97$; $P < 0.0001$; data not shown). Water soluble P varied with TC (Fig. 4). Also, stepwise regressions (data not shown) suggest that OC is associated with high P concentrations in water which is similar to the findings of other researchers. This finding is supported by previous evidences of Maguire and Sims (2002a) that acidic, high OM soils behaved differently from the other soils in their study. However, Dell'Olivo et al. (2008) found that P retention was negatively related to OM. From our initial findings it could be concluded that the relationships among soil tests are location specific and likely dependent on the soil OM. The role of OM in P sorption-desorption characteristics is still not clear (Afif et al., 1995) but it has been reported to be linked to a decrease in P sorption (Barrow, 1989). McDowell and Sharpley (2001) proposed that OM could occupy sorption sites and therefore their grassland soils with larger amounts of OM increased the desorption potential of loosely bound P compared to their arable soils with lower OM. The relationships between TC and WSP (Fig. 4) showed that for wetland soils low values of WSP are found for the lower range (0–12%) whereas higher OM soils were more likely to have higher WSP values. This may be due to the fact that these two soil groups have different solubility patterns and different P retention capacities. Several researchers (Chapman et al., 1997; Fuhrman et al., 2005; Koopmans et al., 2002; Koopmans et al., 2006) have shown that larger soil/water ratios (e.g., 1:50, 1:250) extracted significantly higher P amounts than narrower ratios. Using a different soil/water ratio that would be appropriate for WSP determinations in wetland soils may be a possible option for minimizing the difference in WSP/M1-PSR trends between soils with 0 to 12% TC and soils with >12% TC. We chose 12% TC (or 12% OC for the soils in this study) as the cutoff based on the amount of OC necessary to meet the criterion of “organic soil material” in USDA classification. Some hydric soils indicators are linked to “organic soil material” (e.g., muck presence; Histic epipdon) or “organic soils.”

Phosphorus Saturation Ratio for Wetland Soils

An estimation of the P release potential of soil can be done on the basis of PSR because the parameter is related to the amounts of P extracted by different solutions (Breeuwsma and Silva, 1992; Kleinman et al., 2003; Maguire and Sims, 2002a; McDowell et al., 2001; Nair and Harris, 2004; Nair et al., 2004; Sallade and Sims, 1997; van der Zee et al., 1987). There will be some concern on the use of (Fe + Al) as a surrogate for P sorption in wetland soils since wetland soils contain higher amounts of TC (Table 1). Also, oxidation-reduction changes could play an important part in P solubility and sorption mechanisms in wetlands (Reddy et al., 1998). Further, hydrated Fe oxides associated with Al and OM in gel complexes

Table 1. Mean, SD, and range (maximum [max] and minimum [min] values) for pH, total carbon (TC), total phosphorus (TP), water soluble phosphorus (WSP), Mehlich 1-phosphorus (M1-P), Mehlich 1-iron (M1-Fe), and Mehlich 1-aluminum (M1-Al), Mehlich 3-phosphorus (M3-P), Mehlich 3-iron (M3-Fe), and Mehlich 3-aluminum (M3-Al), and oxalate-extractable P (Ox-P), oxalate-extractable Fe (Ox-Fe), and oxalate-extractable Al (Ox-Al) for all of the samples (by location: center of wetland, edge of wetland, upland) in this study.

| Location | Statistics | pH | TC | TP | WSP | M1-P | M1-Fe | M1-Al | mg kg ⁻¹ | | | | | |
|-------------------|------------|-----|-----|------|------|------|-------|-------|---------------------|-------|-------|------|--------|--------|
| | | | | | | | | | M3-P | M3-Fe | M3-Al | Ox-P | Ox-Fe | Ox-Al |
| Center of wetland | Mean | 5.4 | 97 | 582 | 9.0 | 38 | 158 | 343 | 43 | 206 | 585 | 301 | 4695 | 1889 |
| | SD | 0.9 | 119 | 652 | 25 | 99 | 229 | 292 | 50 | 113 | 332 | 396 | 5573 | 1656 |
| | Max | 9.4 | 483 | 6119 | 236 | 923 | 1837 | 1298 | 330 | 684 | 1488 | 3236 | 35,100 | 15,454 |
| | Min | 3.0 | 6 | 8.5 | 0.1 | 1.2 | 0.3 | 0.4 | 1.6 | 16 | 14 | 17 | 77 | 27 |
| Edge of wetland | Mean | 5.1 | 89 | 509 | 8.0 | 33 | 141 | 330 | 38 | 192 | 572 | 241 | 4178 | 1810 |
| | SD | 0.8 | 107 | 515 | 17 | 90 | 190 | 281 | 44 | 103 | 324 | 271 | 4657 | 1482 |
| | Max | 6.8 | 499 | 4539 | 99 | 783 | 1553 | 1537 | 310 | 527 | 1411 | 2410 | 24,145 | 11,152 |
| | Min | 3.0 | 8 | 3.6 | 0.01 | 0.8 | 0.6 | 0.7 | 1.5 | 7 | 23 | 11 | 75 | 122 |
| Upland | Mean | 4.9 | 37 | 367 | 3.0 | 19 | 60 | 260 | 35 | 145 | 543 | 155 | 2,149 | 1077 |
| | SD | 0.8 | 39 | 344 | 3.8 | 24 | 61 | 172 | 47 | 96 | 319 | 166 | 2,243 | 765 |
| | Max | 7.0 | 256 | 2396 | 21 | 147 | 332 | 758 | 283 | 624 | 1376 | 829 | 10,674 | 4998 |
| | Min | 2.0 | 6 | 25 | 0.04 | 1.0 | 0.1 | 0.3 | 1.8 | 14 | 32 | 11 | 18 | 14 |

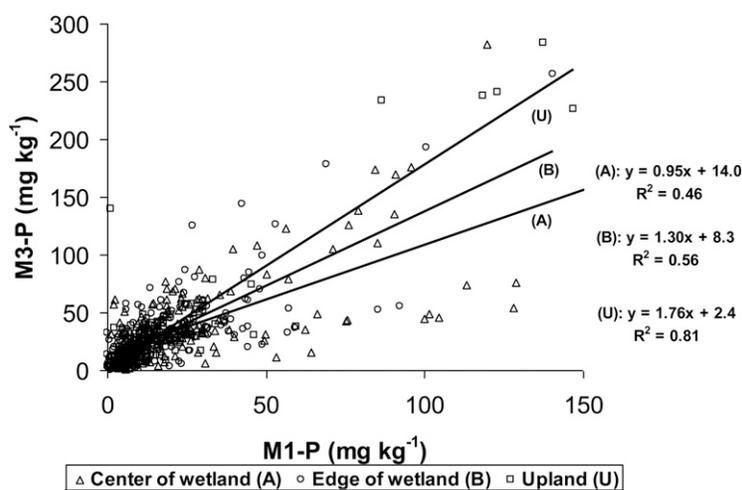


Fig. 3. Relationship of Mehlich 1-phosphorus (M1-P) and Mehlich 3-phosphorus (M3-P) for all soils by location ("A" represents center of wetland, "B" represents edge of wetland and "U" represents upland adjacent to the wetlands; $P < 0.0001$).

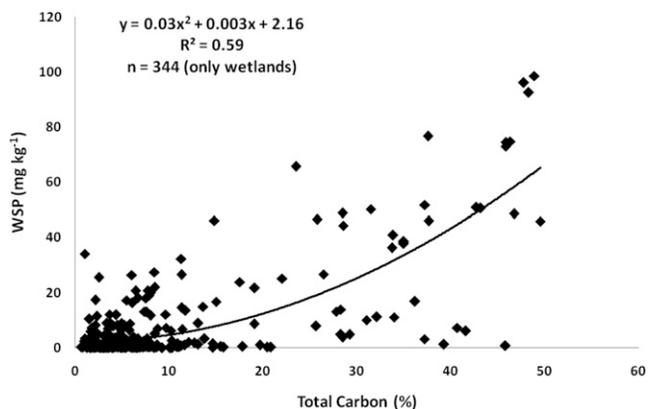


Fig. 4. Correlation between water soluble phosphorus (WSP) and total carbon (TC); $P < 0.0001$; only wetland soils are included.

has been shown to control inorganic P sorption in lake sediments (McCallister and Logan, 1978). Furthermore, Reddy et al. (1998) found that P retention by stream sediments and wetland soils in Florida was strongly correlated with Fe and Al, and that adding total organic C to predictive equations improved

the variability only slightly, that is, from 87 to 92%. For almost all practical purposes it should be possible to use (Fe + Al) as an indicator of P sorption capacity in wetland soils.

Some soil tests could be predictors of soluble P, desorbable P, and PSR (Pautler and Sims, 2000). The Ox-PSR has been suggested as an indicator of P leaching from agricultural soils (Breeuwsma et al., 1995; Hooda et al., 2000; Maguire et al., 2001; Nair and Harris, 2004; Nair et al., 2004). Pautler and Sims (2000) and Nair et al. (2004) have shown that the agricultural soils will meet the adequate crop P supply and environmental protection both at the same time for those soils below an Ox-PSR threshold.

The WSP vs. various PSRs (Fig. 5) show two different TC ranges where there is a need to assign a threshold value or change point above which PSR values suggest environmentally problematic situations. For soils having <12% TC, the threshold PSR appears higher than for the soils having >12% TC. The change point for WSP-PSR relationships for Florida upland soils was 0.1 for WSP/M1-PSR (Nair et al., 2004). The relationships between WSP and M3-PSR or Ox-PSR were similar to the WSP/M1-PSR relationship (Fig. 5) with the change

point being lower for soils with >12% TC, that is, the change point is expected to be lower for wetland soils with higher organic C (Table 1). For upland soils, threshold PSR calculations with Mehlich 3 parameters was 0.8 and with oxalate parameter, 0.1 (Nair et al., 2004). Recent work on upland soils (Chrysostome et al., 2007b) has shown that the extraction ratio used in WSP determinations (1:10 soil/water in this case) would affect the WSP-PSR relationship, but the change point would remain unchanged. For wetland soils, a protocol for determining WSP may have to be established before WSP can be used as an indicator of P release from the soil.

Environmentally Based Critical Soil Test Phosphorus

One of the major questions of interest is defining the upper, environmentally based limit for an STP such as M1-P and M3-P that could be used in evaluating the water quality in a wetland. An upper TP limit could be set for environmentally sound wetland conditions. The background concentration of TP for all of the wetland soils of this study is approximately 550 mg kg⁻¹ calculated from the 75th percentile of the distribution of all the unimpacted wetland soils of this study according to USEPA guidelines (USEPA, 2000a).

Total P also gave a significant regression coefficient ($R^2 = 0.62$, $P < 0.0001$) against Ox-PSR with a polynomial second order curve (Fig. 6a). Total P is not currently used as one of the STPs or as an indicator of environmentally available P. However some researchers (Pautler and Sims, 2000) have shown that a percent of easily desorbable P could be calculated by using the ratio of Ox-P: TP and could be used as an indicator of P release to the surrounding water bodies. They suggested that the impacted soils with low concentrations of [Ox-Fe + Ox-Al] could be susceptible to P leaching. In our study, approximately 50% (Ox-P = 0.50 [TP] - 12, $R^2 = 0.86$, $P < 0.0001$, $n = 357$) of TP in wetland soils is oxalate extractable, suggesting that a significant amount of the TP might have the potential to be released to the water column. Based on the reference background concentration of TP = 550 mg kg⁻¹ the threshold values for Ox-PSR will be 0.079 ($R^2 = 0.62$, $P < 0.0001$, $n = 344$) (Fig. 6a).

Soil test P is a common determination in Florida in both private and public laboratories (Nair et al., 2004). For upland soils it is well established that M1-P and M3-P are strongly correlated to neutral salt solution, or extracted by neutral salt solutions (Maguire and Sims, 2002a, 2002b; McDowell et al., 2001; McDowell and Sharpley, 2001; Pautler and Sims, 2000; Sims et al., 2000; Sotomayor-Ramirez et al., 2004). Therefore, there is an increasing trend to relate WSP to PSR analyses for predictive purpose (Nair and Harris, 2004; Nair et al., 2004; Pautler and Sims, 2000). Since M1-P is Florida's soil test P, M1-P to PSR relationship was studied for wetland soils. The M1-P was significantly related to Ox-PSR with a second order polynomial curve ($R^2 = 0.86$, $P < 0.0001$) for all our wetland soils (Fig. 6b). Using the threshold Ox-PSR as 0.079, M1-P and M3-P (Fig. 6b and 6c) were calculated. Similar relationships have been drawn by the change point technique to detect the change point for upland soils (Nair et al., 2004; Pautler and Sims, 2000) for M1-P and Ox-PSR. In our case there is a lack

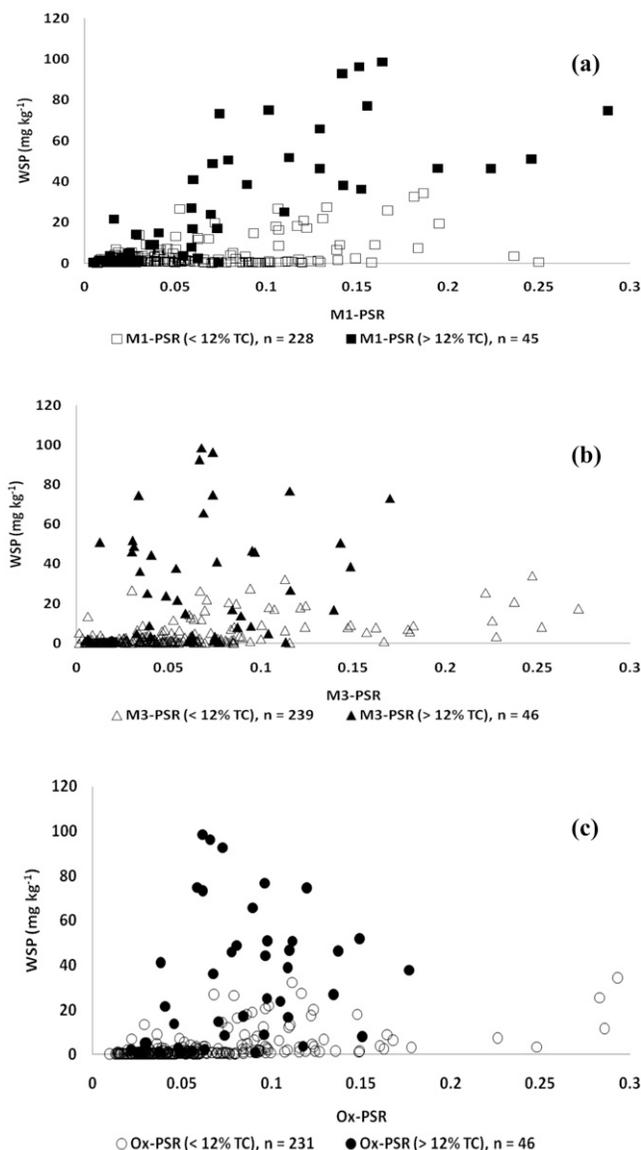


Fig. 5. Water-soluble phosphorus (WSP) as a function of (a) M1-PSR (b) M3-PSR, and (c) Ox-PSR for wetland soils with <12 and >12% total carbon (TC).

of data points showing a linear increase in STP (Fig. 6b); the better fitted second degree curvilinear line has been drawn.

Sallade and Sims (1997) found that M1-P was significantly correlated to P release ($r = 0.52$, $P < 0.0001$ at 35°C) in a sediment/water flux study. The researchers noted that sediments with similar biologically available P (BAP) and phosphorus saturation index (PSI) values did have different PSRs and concluded that the PSR could be used to target ditch sediments with higher potential to release P to overlying waters.

There is a strong correlation between M1-PSR and Ox-PSR for the center of wetland and edge of wetland; the correlation between M3-PSR with both M1-PSR and Ox-PSR is not as strong for soils of the center and edge of wetlands (Table 2). However, M1-PSR, M3-PSR, and Ox-PSR all are significantly correlated among each other for upland soils which agrees with the findings of Nair et al. (2004). Based on this study M1-PSR

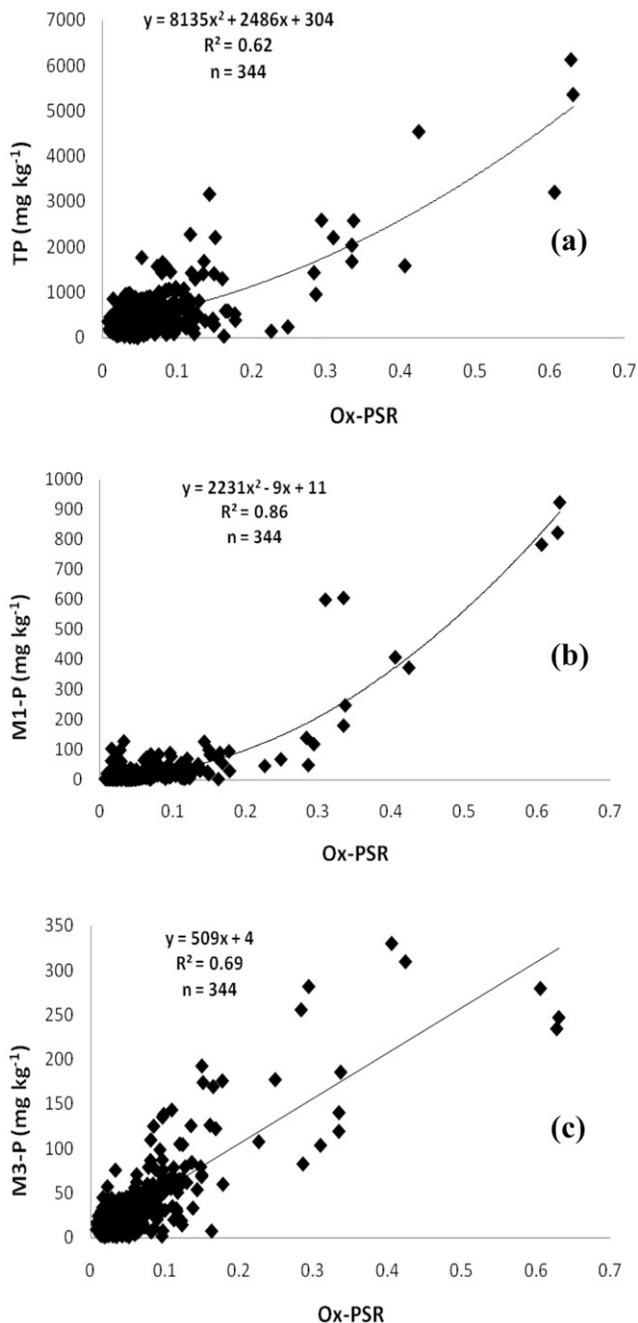


Fig. 6. (a) Total P as a function of oxalate-phosphorus saturation ratio (Ox-PSR) for all wetland soils, $P < 0.0001$. (b) Mehlich 1-phosphorus (M1-P) as an indicator of wetland soil's P release trend based on its relationship with oxalate PSR (Ox-PSR); $P < 0.0001$. (c) Mehlich 3-phosphorus (M3-P) as an indicator of P release from wetland soils based on its relationship with Ox-PSR, $P < 0.0001$.

and Ox-PSR may be appropriate for use as potential P release indicators for wetland soils. Using the equations in Table 2, the threshold M1-PSR for P release for the wetland soils (center) is 0.129 and the same for M3-PSR is 0.078. Although the equation used in M3-PSR calculated is highly significant ($P < 0.0001$), the correlation is poor ($R^2 = 0.44$). Based on the reference background TP concentration of 550 mg kg^{-1} (75th percentile distribution) of the wetlands surveyed (center and

Table 2. Phosphorus saturation ratio (PSR) comparison† by location.

| Location | PSR | | N | Equation |
|-----------------------|-------------|--------|-----|------------------------|
| | Comparison | R^2 | | |
| Center of wetland (A) | M1‡ vs. M3§ | 0.2591 | 201 | $y = 0.0536x + 0.0519$ |
| | M1 vs. Ox¶ | 0.7425 | 175 | $y = 0.5147x + 0.0337$ |
| | M3 vs. Ox | 0.437 | 177 | $y = 1.0586x + 0.0171$ |
| Edge of wetland (B) | M1 vs. M3 | 0.2376 | 204 | $y = 0.0341x + 0.0472$ |
| | M1 vs. Ox | 0.6138 | 182 | $y = 0.2591x + 0.0446$ |
| | M3 vs. Ox | 0.6174 | 180 | $y = 1.304x + 0.0012$ |
| Upland (U) | M1 vs. M3 | 0.7733 | 120 | $y = 0.6367x + 0.0111$ |
| | M1 vs. Ox | 0.6192 | 118 | $y = 0.8189x + 0.0202$ |
| | M3 vs. Ox | 0.6942 | 120 | $y = 1.1388x + 0.0123$ |

†All R^2 values are significant at $P < 0.0001$; the first parameter is "x" and the second, "y" in the equations.

‡ M1 = Mehlich 1.

§ M3 = Mehlich 3.

¶ Ox = oxalate.

edge), threshold values for P release to the surrounding water bodies were estimated to be: M1-P = 24 mg kg^{-1} , M3-P = 44 mg kg^{-1} , Ox-PSR = 0.079, M1-PSR = 0.101, and M3-PSR = 0.067. For wetland soils (center and edge) the following equations were used for M1-PSR and M3-PSR calculations:

$$\text{Ox-PSR} = 0.4129(\text{M1-PSR}) + 0.0375 (R^2 = 0.42; P < 0.0001) \quad [2]$$

$$\text{Ox-PSR} = 0.8666(\text{M3-PSR}) + 0.0229 (R^2 = 0.50; P < 0.0001) \quad [3]$$

Although the WSP procedure used in the determination may not be the most appropriate, it appears that the threshold PSR values calculated using an alternate procedure are reasonable as compared to the WSP/PSR relations for wetland soils shown in Fig. 5. The threshold M3-PSR should be less than that for M1-PSR or Ox-PSR.

Conclusions

Our initial findings comparing different soil tests with water soluble P suggests that P could be sorbed loosely on the OM and that might be a reason for high amounts of WSP in wetland soils. There is a limited amount of data on wetland soils to establish a numeric value but center of wetland soils in this study showed a wide range of WSP with a mean concentration of 9 mg kg^{-1} . Our stepwise regressions (data not shown) suggest that OM is one of the causes of high P concentrations in water which is similar to the findings of other researchers. However, concentration of Fe, Al, pH, and fertilization also could play a big role in governing P concentration of wetland soils. The poor correlation between different STP and water extraction is attributed to the wetland soils having high organic matter. Water soluble P determinations on wetland soils were performed on dry soils at a 1:10 soil/solution soils which may not be the most appropriate method for its determination as a wetland P release indicator.

The background TP concentration of all the wetlands of this study is approximately 550 mg kg^{-1} which was calculated from the 75th percentile of the distribution of all minimally impacted wetland soils of this study according to USEPA guidelines. In response to the need to implement numeric criteria for nutrients for protecting a water body, our research demonstrates a possible application of STP methods and how threshold values may be as-

signed to the identified indicators for protection of water quality in a wetland. Based on the reference background concentration (TP = 550 mg kg⁻¹) of the wetlands surveyed, threshold values for P release to the surrounding water bodies were estimated to be: M1-P = 24 mg kg⁻¹, M3-P = 44 mg kg⁻¹, O_x-PSR = 0.079, M1-PSR = 0.101, and M3-PSR = 0.067. These values are, however, only a first approximation and will have to be re-evaluated when additional data become available.

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