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Sediment phosphorus dynamics for three tile fed drainage ditches in Northeast Indiana[☆]

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Abstract

Phosphorus (P) losses from agricultural lands degrade surface waters due to anthropogenic eutrophication. Previous studies focused on plot-to-field scale P loss and reductions from best management practices (BMP's), little information in intense agricultural catchments has been gathered on the dynamics influencing P beyond the edge of the field. This study was conducted to examine the phosphorus equilibrium between the water column and sediments in three tile fed drainage ditches in Northeast Indiana. Surface water and sediment samples were collected and analyzed for organic carbon (C), particle size and P from sites along three ditches with similar soils and land use at sites within each watershed draining approximately 300 and 1500 ha on each ditch. Organic C, silt and clay fractions of the bottom sediments decreased with increasing drainage area. Soluble P concentrations were low in Ditch A, but increased with increasing drainage area (0.02–0.05 mg P L⁻¹). Overall, the P concentrations were higher in the Ditches B and C (0.06–0.09 mg P L⁻¹). Exchangeable P, P partitioning index and equilibrium P concentrations (EPC₀) decreased with increasing drainage area by as much as 95, 93 and 100%, respectively, except in one catchment area with a confined animal feeding operation between sampling points, where ExP and EPC₀ increased by 4 and 116%, respectively. Aluminum sulfate and calcium carbonate treatment of ditch sediments reduced exchangeable P and sediment EPC₀ in this study. Results from this study indicated some watershed characteristics, as well as sediment physiochemical properties, affect ditch sediment

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and water P equilibrium and buffering capacity. Furthermore, this study demonstrated that managers could potentially use chemical treatment of the ditches to increase the temporary retention of P in ditches and maybe reducing sediment P availability.

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1. Introduction

Phosphorus losses from agricultural production operations have been implicated in the eutrophication of surface waters (Carpenter et al., 1998). This can be particularly problematic in drinking water supplies, as some algae and actinomycetes release organic compounds (i.e., geosmin and 2-methylisoborneol) giving drinking water an earthy taste and odor that is aesthetically displeasing (Napolitano et al., 1996; Sivonen, 1982). Despite research efforts and best management practices (BMP's) to minimize P losses from agricultural lands (Shreve et al., 1995; Smith et al., 2004), water quality problems associated with agricultural P sources and anthropogenic eutrophication persist.

Phosphorus is lost to surface waters in many forms, including ortho-phosphates, poly-phosphates and P bound in particulate matter (Sharpley and Moyer, 2000). These compounds impact surface water quality to varying degrees depending on their bioavailability or the potential for microbial or algal P uptake. After P reaches surface waters from landscape sources, the soluble P concentration will depend on the form of P entering the water and phosphate equilibrium with benthic sediments (Meyer, 1979; Koltz, 1988). Sediment associated microbes may also enhance the ability of streams to buffer P inputs (Haggard et al., 1999) and influence stream sediment and water phosphate equilibrium (Klotz, 1985; Klotz, 1991). Physiochemical characteristics of bottom sediment such as particle size distribution, exchangeable Al, organic matter (OM) content and mineralogy also affects the ability of streams to temporarily retain P and regulate dissolved P concentrations (Haggard et al., 1999; Klotz, 1985; Froelich, 1988). P concentrations generally increase with the proportion of agricultural land use in a stream's drainage area, where row crops may contribute particulate bound P or ortho-phosphates from fertilizer sources and land receiving manure from confined animal feeding operations (CAFO's) may contribute dissolved and organic P. The relation between land use and stream water and sediment P is often suppressed by P inputs from municipal wastewater treatment plants (Fox et al., 1989). Stream P retention efficiency is greatly reduced downstream from wastewater treatment plants, including specific mechanisms such as sediment P buffering capacity (Haggard et al., 2001).

Phosphorus equilibrium between sediments and water may play an important role in the transport and temporary retention of P in these drainage systems (Froelich, 1988). It is important to understand the dynamics between ditch sediments and water to determine if these systems are acting as a source, sink or regulator of dissolved P concentrations.

Aluminum can be used to remove dissolved P by precipitation (Smith et al., 2001) and aluminum phosphates are more physiochemically stable than iron or calcium phosphates. Addition of aluminum sulfate (alum) to lakes has been shown to reduce the P concentrations in the water column (Welch et al., 1982; Welch and Schriever, 1994). It may

be possible to remove dissolved P from the water column of ditch sediments by adding chemical treatments such as aluminum sulfate (alum) to the sediments. If this practice can be verified, it may then be possible for watershed managers to apply the practice in problem areas within the watershed.

The objectives of this study were: (1) to evaluate water and sediment equilibrium in three tile fed drainage ditches in Northeast Indiana; (2) to determine whether ditch sediments are a potential source or sink of P in this aquatic system; and (3) to assess the effects of chemical treatment on the P equilibrium and buffering capacity of ditch sediments.

2. Materials and methods

Sediment-water P equilibrium and buffering capacity were characterized at sites corresponding with the Indiana Source Water Protection Initiative research watersheds in the St. Joseph River Watershed (Figs. 1 and 2). Water quality is continuously monitored by collection of samples from ISCO samplers at seven sites in three ditches (Table 1). Three samplers are located on Ditch A, and two samplers each on Ditches B and C in a nested



Fig. 1. Map of the St. Joseph River Watershed, which covers portions of Michigan, Ohio and Indiana.

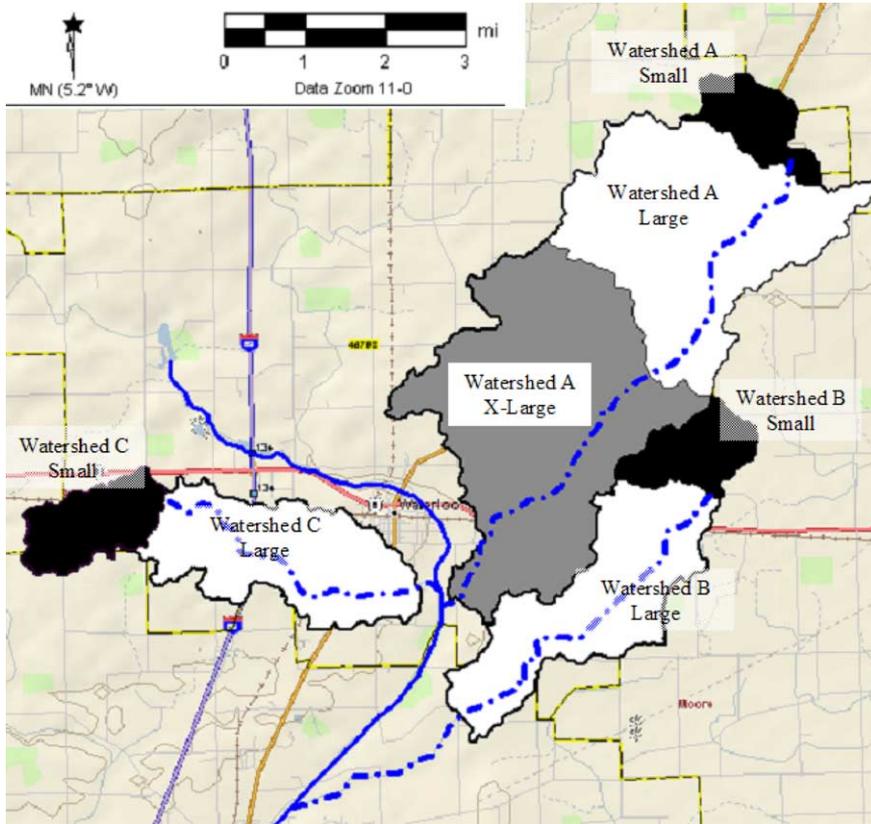


Fig. 2. Map of three nested watersheds within the St. Joseph River Watershed of Northeast Indiana.

paired watershed design (Table 1). A CAFO was located within Ditch C between the small and large sampling sites.

Surface water and sediment were sampled approximately 5 m downstream of each sampling site used for water quality monitoring. Eight liters of surface water were collected from each site prior to sediment sample collection and placed in plastic containers for transport to the laboratory. A 60 mL water sample from each site was filtered through 0.45 μm membrane filters in the field, and acidified. Approximately 2 L of sediment samples were collected by removing the surface 3 cm of benthic sediments, placing the sediments into 1 L plastic containers, and filled the remaining void with ditch water. Samples were transported and stored at 4 C until extractions and analysis could be performed.

Sediments from each site were sieved to pass a 2.0 mm mesh sieve, then placed in a 1 L plastic bottle until ready for use. The bulk water samples from each site were filtered through 0.45 μm membrane filters into 1 L aliquots, which were then spiked with +0.00, +0.10, +0.25, +0.50 and +2.00 mg P L^{-1} for subsequent P adsorption experiments to be performed on the sieved sediment samples. As an example, if the water from a site

Table 1
Identification of sampling sites on the three watersheds, and description of the soils and land use for those areas

ID	Area (ha)	Major soils	Land use/cropping
A-Small	299	Rawson sandy loam, Pewamo silty clay, Morley silty clay loam, Blount silt loam	79% Agriculture 15% Grass/pasture 4% Forest
A-Large	1936	Blount silt loam, Pewamo silty clay, Glynwood loam, Rawson sandy loam, Morley silty clay loam	77% Agriculture 16% Grass/pasture 6% Forest
A-Xlarge	4307	Blount silt loam, Pewamo silty clay, Glynwood loam, Rawson sandy loam, Rensselaer loam, Sebewa sandy loam	78% Agriculture 14% Grass/pasture 6% Forest
B-Small	311	Blount silt loam, Pewamo silty clay, Glynwood loam	85% Agriculture 8% Grass/pasture 6% Forest
B-Large	1418	Blount silt loam, Pewamo silty clay, Glynwood loam, Sebewa sandy loam, Rensselaer loam	83% Agriculture 12% Grass/pasture 3% Forest
C-Small	373	Glynwood loam, Blount silt loam, Pewamo silty clay	83% Agriculture 10% Grass/pasture 4% Forest
C-Large	1381	Blount silt loam, Pewamo silty clay, Glynwood loam, Morley silty clay loam	73% Agriculture 17% Grass/pasture 5% Forest

contained 0.05 mg P L^{-1} , there would be five 1 L samples with the following P concentrations: 0.05, 0.15, 0.30, 0.55 and 2.05 mg P L^{-1} .

To determine the most labile fraction of P, approximately 25 g of wet sediment were placed into a 250 mL centrifuge tube, to which 100 mL of 1 M MgCl_2 were added, shaken for 1 h and filtered through $0.45 \mu\text{m}$ membrane filter after centrifuging (Ruttenburg, 1992; Haggard et al., 1999). A 20 mL aliquot of this sample was analyzed using inductively coupled argon plasma (ICAP) spectrophotometry. Dry weight from each sediment sample was determined gravimetrically. This represents the fraction that would desorb from the ditch sediments first if the sediments act as an internal source of P. Exchangeable P (ExP) was calculated from the concentration of P in the MgCl_2 extraction. A partitioning index was calculated by dividing the ExP in 1 g of ditch sediment by the P in 1 mL of ditch water (Triska et al., 1994).

An adsorption/desorption experiment was conducted to determine the equilibrium P concentration (EPC_0) and the P buffering capacity (K) for each sediment. Sediment EPC_0 is the P concentration at which there is no net adsorption or desorption by the sediments

(Taylor and Kunishi, 1971). Twenty-five grams of wet ditch sediment was shaken on a reciprocating shaker at 180 cycles min^{-1} with 100 mL of P-spiked ditch water for 1 h. All equilibrations were conducted in triplicate, filtered (0.45 μm) and total soluble P concentration determined by ICAP spectrophotometry. Sediments were then dried to obtain a dry mass associated with each sample, and were used for calculation of P adsorption parameters. These samples were analyzed using ICAP spectrophotometry to determine total soluble P concentrations. Soluble P concentrations from these samples were used to calculate the EPC_0 by regressing the amount of P sorbed by the sediments against the initial P concentration of each sample. With P sorbed as the dependent variable, the point at which there is neither net P adsorption nor desorption, is the equilibrium P concentration.

To determine the impacts of chemical amendments on P equilibrium and buffering capacity in ditch sediment, 0.5 g of aluminum sulfate ($(\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O})$) and 0.5 g of calcium carbonate (CaCO_3) were added to approximately 250 g wet sediments. The procedures detailed above were performed on the aluminum sulfate and calcium carbonate treated sediments to determine if the chemical treatments could increase P retention in tile fed drainage ditches and reduce P transport to receiving waters.

Partitioning index and ExP data were analyzed statistically using analysis of variance procedures in SAS v 8.0 (SAS Institute, Cary, NC). Means were separated using Fisher's protected LSD. Equilibrium P concentration, and buffering capacity were analyzed using regression techniques from the sorption isotherm data. Correlation coefficients (R^2) used in calculation of EPC_0 were all above 0.91, and were significant at $P < 0.05$.

3. Results and discussion

Organic C, silt and clay content of ditch sediments decreased with increasing drainage area (Table 2). At the small sites, organic C content of ditch sediments was $>6\%$, while at the large sites, the range was 1–3%. The small sites contained water year round; however during dry periods, this water may be stagnant. Reduced discharge and possibly stagnant waters in ditches draining smaller areas would also decrease the amount of organics and/or smaller particulates carried downstream due to decreased flow velocity and thus energy to transport particulates. This is demonstrated also by the particle size distribution of ditch sediments, where the silt and clay fractions were greater at the small sites than the large sites.

Table 2
Organic matter content and particle size distribution of benthic sediments from ditches by collection site

Watershed	Site	Organic C (%)	Sand (%)	Silt (%)	Clay (%)
A	Small	8.78	31.4	59.1	9.5
	Large	1.44	92.6	4.6	2.8
	Xlarge	0.89	95.9	2.8	1.3
B	Small	6.16	13.2	51.4	35.4
	Large	3.14	78.9	10.4	10.7
C	Small	11.4	8.7	50.1	41.2
	Large	1.40	90.2	6.2	3.6

Table 3
Soluble phosphorus and nitrogen concentrations in drainage ditches

Watershed	Site	P (mg L ⁻¹)	NH ₄ (mg L ⁻¹)	NO ₃ (mg L ⁻¹)
A	Small	0.02	0.09	7.14
	Large	0.03	0.11	11.24
	Xlarge	0.05	0.17	11.99
B	Small	0.08	0.07	13.42
	Large	0.06	0.08	6.77
C	Small	0.06		2.25
	Large	0.09	0.12	5.66

There were only moderate changes between soluble P and NH₄ concentrations in ditch water when comparing the sampling sites as drainage area increased within Watersheds A and B (Table 3). The greatest change in aqueous P concentration between sites was between the small and large sites of Ditch C (0.03 mg P L⁻¹). This is an interesting observation, because it is the largest change in P concentration between sites, and it is also the only site with a runoff and subsurface flow being collected from a CAFO between sampling sites. Nitrate-N concentrations in ditch water increased 50–150% as catchment area increased between sites in Ditches A and C, whereas NO₃ concentrations decreased 50% between sites as drainage area increased in Ditch B. Nitrate concentration increases in Ditches A and C may have resulted from contributions from on-site septic systems in Ditch A and the CAFO in Ditch C. The reduction in NO₃ concentration was likely due to dilution, as houses are located directly upstream (within 100 m) of the small site on Ditch B, however there are not any houses with known septic systems between the small and large sites on this ditch.

Exchangeable P in the ditch sediments decreased with increasing area drained at Watersheds A and B; however ExP slightly increased from 1.72 to 1.79 mg P kg⁻¹ sediment within Watershed C. The general reductions in sediment ExP as drainage area increased was likely due to concomitant changes in particle size distribution and organic matter content of ditch sediments. These parameters often influence the ability of sediments to retain P (Koltz, 1988; Haggard et al., 1999; Tedesco et al., 2003). Just as the particle size distribution can impact the anion exchange capacity (AEC), and the concomitant P sorption capacity of soils and sediments, so can organic matter content (Marcos et al., 1998). The AEC controls P sorption, as common soil anions are sorbed in the order HPO₄²⁻ > SO₄²⁻ > NO₃⁻ = Cl⁻ (Tisdale et al., 1985). In contrast, the increase in ExP in Watershed C with increasing drainage area was consistent with increased soluble P concentrations of the water column of the ditch. It is conceivable that the CAFO influenced both sediment and water P concentrations because P concentrations increased with decreases in certain sediment physiochemical properties. The ExP in the small site on Ditch C were the 'cleanest' with respect to P for any of the small watersheds, while the large site on Ditch C had the greatest ExP levels of any of the large sites. This data suggests that the CAFO did influence the ditch P dynamics by transforming sediments with low background labile P levels to high labile P levels of similar particle size distribution and organic matter content.

Table 4
Exchangeable P (ExP), partitioning index, equilibrium P concentration and K for ditch sediments from three different watersheds before and after alum treatment

Watershed	Site	ExP ^a		Partitioning index ^a		EPC _o		K	
		Initial (mg P kg ⁻¹)	Alum treated (sediment)	Initial (g H ₂ O g ⁻¹)	Alum treated (sediment)	Initial (mg P L ⁻¹)	Alum treated (H ₂ O)	Initial (L H ₂ O kg ⁻¹)	Alum treated (sediment)
A	Small	4.79Bz	2.50Ay	240Az	125Ay	0.078	0.017	1.34	1.37
	Large	1.01CDz	0.43Cz	33.7Cz	14.4Bz	0.055	0.008	0.533	0.568
	Xlarge	1.57Cz	0.17Cy	31.5CDz	3.4By	0.067	-0.002	0.412	0.520
B	Small	9.35Az	1.73ABy	117Bz	21.6By	0.050	-0.023	1.07	1.07
	Large	0.49Dz	0.59Cz	8.1Dz	9.9Bz	-0.020	-0.001	0.601	0.587
C	Small	1.72Cz	1.08BCz	28.7CDz	18.0Bz	0.051	0.004	1.85	4.18
	Large	1.79Cz	0.72Cy	19.9CDz	8.0Bz	0.110	-0.011	0.518	0.499

^a Common letters within a column indicate no significant difference at $P < 0.05$. Common letters within a row indicate no significant difference at $P < 0.05$.

Aluminum sulfate and calcium carbonate additions to sediments reduced ExP in all samples, except one site where a slight increase from 0.5 to 0.6 mg P kg⁻¹ was observed (Table 4). In Ditch A, reductions in ExP ranged from 48 to 89% in the chemically treated sediment compared to the untreated ditch sediments. Similar reductions (37–60%) were noted in ditch sediments from Watershed C. As with the untreated ditch sediments, there was a trend of decreasing ExP in the chemically treated sediments with increasing drainage area.

The partitioning index was as much as one order of magnitude higher in sediments from the small site of Watersheds A and B compared to the large sites in the same ditches (Table 4). In Watershed A, there were minimal differences between the large and X-large sites for the partitioning index. Smaller changes in the partitioning index were exhibited in Watershed C reflecting changes in sediment and water P; the reduction in the partitioning index from about 29–20 represented about a 30% decrease. Alum additions to sediments tended to reduce the partitioning index by approximately 50–90%, with the one exception of the large site on Ditch B. The slight increase in partitioning index was due to the reduced amounts of ExP in the sediments both before and after alum, and the slight increase in ExP following the alum treatment. In Ditch A, where there was only minimal difference in the partitioning index between the large and X-large sites, treatment of sediments with alum resulted in greater decreases in the partitioning index in the X-large site than the large site.

Correlation coefficients for the regression equations used to calculate EPC_o were all above 0.98, with the exception of the untreated sediments from the Ditch C small site ($R^2 = 0.91$) and alum amended sediments from the Ditch B small site ($R^2 = 0.93$; data not shown). To determine if sediments are a source, sink or in equilibrium with the P concentrations in the water column, one can plot the water column dissolved P concentration against the sediment EPC_o values (Fig. 3). Points that lie above a 1:1 line indicate that the sediments

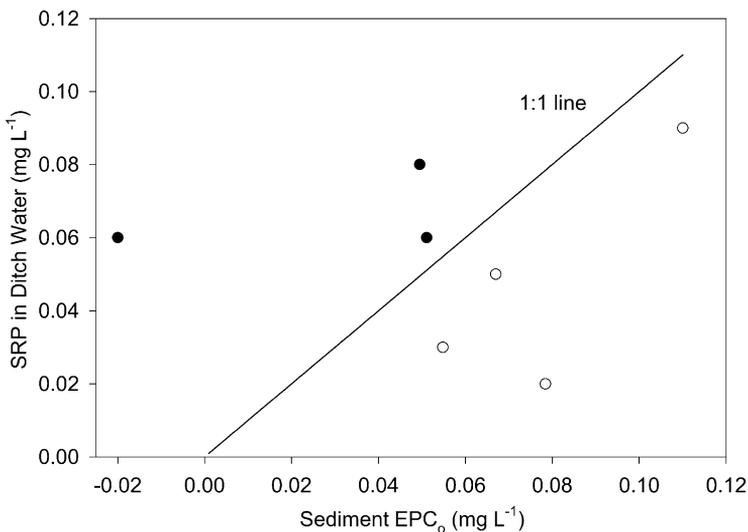


Fig. 3. Soluble P in the ditch water plotted as a function of sediment equilibrium P concentration for sediments that act as a potential P source (○) or P sink (●).

will act as a sink for P in the water column, while points that are below the 1:1 line indicate that the sediments act as a source for P in the water column (House et al., 1995). The sediments and water column are in equilibrium at points that lie directly on the 1:1 line in this graph.

In Watershed A, sediment EPC_o ranged from 0.055 at the large site to 0.078 at the small site (Table 4). There was a decrease between the small and large sites within Ditch A, however there was a slight increase in ditch sediment EPC_o between the large and X-large sites. Water column P concentrations were less in Watershed A than ditch sediment EPC_o , indicating that the sediments have the potential to release P to the water column. This could be one explanation for the increase in soluble P concentration with increasing drainage area for Ditch A. When alum was added to sediment, the sediment EPC_o was reduced to levels below the water column P concentration, which could thereby provide one mechanism to reduce P in the water, thereby delivering cleaner water downstream. When the chemical treatments were made the large and X-large sites, as with the partitioning index, there were greater reductions in sediment EPC_o for the X-large site than the large site. This observation leads us to the hypothesis that ditch managers could potentially treat stretches of these ditches further downstream with alum and calcium carbonate and obtain greater reductions in P transport to receiving waters resulting from greater retention of P in the sediments. Further investigation is needed on a meso- and watershed scale to ensure chemical treatment will work in these ecosystems. Potential variables that should be studied include how flow rates, and concomitant sediment/water contact time might impact P sorption/desorption by sediments, if an entire ditch should be treated with alum and calcium carbonate or if this treatment can be targeted to affected areas (such as those stretches receiving runoff from CAFO's). Rates of chemical application and temporal efficacy of these treatments should also be investigated at the meso- and watershed scale.

In Watershed B, sediment EPC_o was 0.05 mg L⁻¹ or less at both sites, with the large site having an EPC_o near 0 mg L⁻¹. In this ditch, P concentrations in the water were greater than sediment EPC_o , indicating that the sediments were acting as a sink of P in the water column. Sediment EPC_o and water column soluble P concentrations were less at the large site compared to the small site. As with results from Ditch A, addition of aluminum sulfate and calcium carbonate reduced sediment EPC_o to concentrations near 0 mg L⁻¹.

Sediment EPC_o in Watershed C ranged from 0.05 at the small site to 0.11 in the large site, corresponding to increases in soluble P concentrations in the water column. The relationship between sediment EPC_o and water column soluble P concentration at this ditch was not consistent at the two sites. At the small site, sediments were a potential sink of P, whereas the sediments were a potential P source further downstream. One possible explanation for this observation could be P enrichment of the sediments from the CAFO during rainfall events, which releases P to water during 'baseflow' conditions. Similar observations have been made downstream from municipal wastewater treatment plants that emit P in effluent (Fox et al., 1989; Haggard et al., 2004). As with the other two watersheds, aluminum sulfate and calcium carbonate additions to sediments from Ditch C reduced sediment EPC_o to concentrations very near 0 mg P L⁻¹.

When sediment EPC_o was regressed against the clay and silt size fractions of the sediments, a strong correlation existed for sites where the sediments were a potential P sink ($R^2 = 0.99$; Fig. 4). Dissolved P will react readily with Al and Fe surfaces on clays that

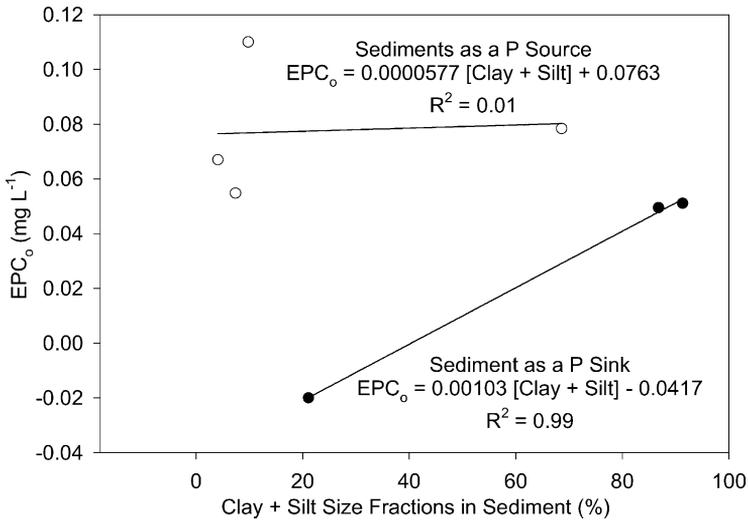


Fig. 4. Equilibrium P concentration as affected by clay and silt size fractions in sediment when the sediments act as either a potential source (○) or a sink (●).

result from weathering of soils (Froelich, 1988). Clay fractions in soils, and thus in ditch sediments, in this area of Northeast Indiana are relatively high in Fe and Al. When sediments are adsorbing P from the water column, one factor that will determine the rate of the reaction will be the surface area of sediments that are 'reactive'. This relationship will not necessarily hold true when sediments are acting as a source of P to the water column as observed by the poor relationship noted in Fig. 5 ($R^2 = 0.01$). While the surface area of sediments would be important for desorption of P from sediments, other variables may play a role in P desorption including the relative difference between the EPC₀ and the SRP in the ditch water at the site, and how tightly bound P is to the sediments.

A relative measure of the ability of the sediment to buffer P from aqueous solutions is the slope (*K*) resulting from the regression to calculate EPC₀ (Table 4). *K* was greater at the small sites, suggesting ditch sediments at this site has a greater P buffering capacity. Organic matter content and fine particle size fractions were strongly related to changes in *K* across all sites (Fig. 5), regardless of whether ditch sediments were a potential P source or sink. These regressions hold up due to the affinity of the organic matter for P and the relative surface areas available to adsorb P from the water column. The presence of organic matter, while likely related to changes in the particle size distribution and discharge as drainage area of the ditch increased, explained 14% more of the variability in *K* than the fine particulate size mineral fractions ($R^2 = 0.98$ and 0.84 , respectively). Organic matter generally has pH dependant anion exchange capacity (AEC), and affinity for the P in the organic matter than the sediments. When alum was added to the sediments, there was relatively little change in the P buffering capacity. These data indicate that the chemical treatments only shift the EPC₀ towards 0 and may have little impact on the ability of sediments to adsorb P per unit increase in P concentration in the aqueous solution. The shift noted here could be as a result of the chemical precipitation of the labile P into aluminum

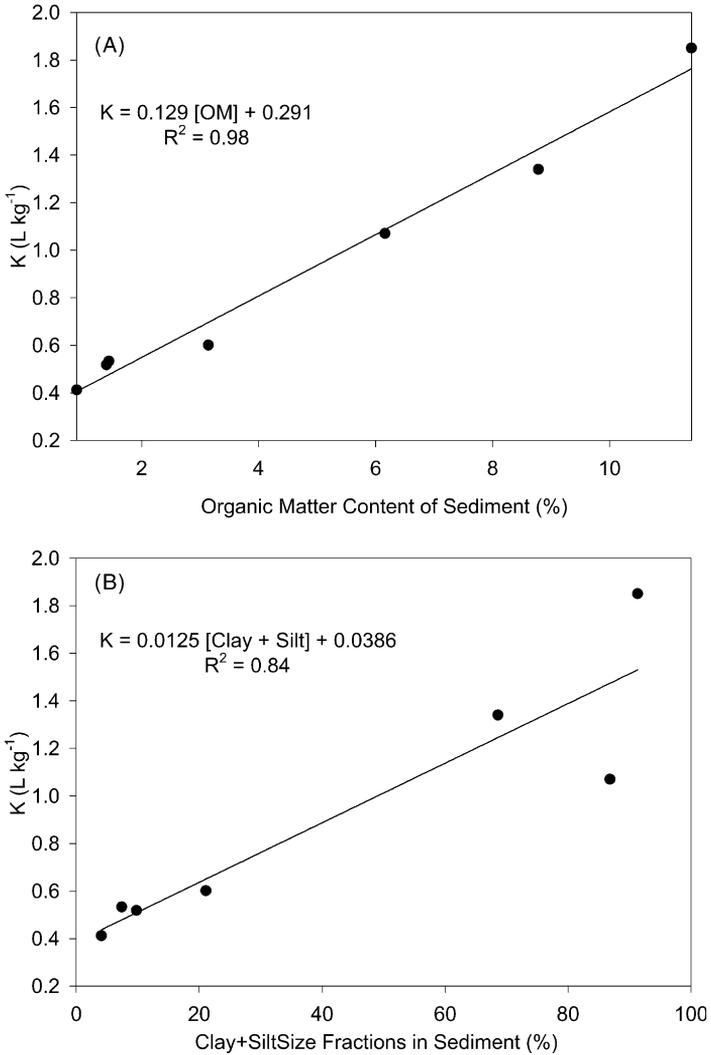


Fig. 5. Slope of regressions (K) from calculation of EPC_o expressed as a function of: (A) organic matter content of ditch sediments and (B) clay + silt size fractions of ditch sediments.

phosphates, allowing the ‘new’ P added to the system to adhere to the sites previously held by the ExP. Further testing needs to be done to confirm this hypothesis.

4. Conclusions

Exchangeable P in ditch sediment generally decreases with increasing area drained, most likely due to an increase in the particle size distribution and a decrease in the amount of organic matter to bind P. Decreasing ExP resulted in decreases in the partitioning index

in Watersheds A and B, indicating greater amounts of loosely bound P in the sediments than in the water column. Analysis of EPC_o values indicated that the ditch sediment acted as a source (Ditch A and large site in Ditch C) and as a sink (Ditch B and medium in Ditch C) for P. Particle size distribution and organic matter content of ditch sediments did not appear to impact EPC_o concentrations as a whole. However, when sediments were separated into 'sources' and 'sinks', there was a correlation between EPC_o and particle size distribution for those sediments that acted as a P sink to the water column. Addition of alum to ditch sediments decreased ExP by 50–90%, the partitioning index by 50% and the EPC_o to values very near, or below 0. These data indicate that watershed managers could potentially use chemical treatments with alum and calcium carbonate to remove P from the water column, thereby delivering cleaner water downstream. Analysis of data between the medium and large sites in Watershed C indicate that land use may have a significant impact on P dynamics in managed ditches.

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