



IMPACT OF DREDGING ON PHOSPHORUS TRANSPORT IN AGRICULTURAL DRAINAGE DITCHES OF THE ATLANTIC COASTAL PLAIN¹

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ABSTRACT: Drainage ditches can be a key conduit of phosphorus (P) between agricultural soils of the Atlantic Coastal Plain and local surface waters, including the Chesapeake Bay. This study sought to quantify the effect of a common ditch management practice, sediment dredging, on fate of P in drainage ditches. Sediments from two drainage ditches that had been monitored for seven years and had similar characteristics (flow, P loadings, sediment properties) were sampled (0-5 cm) after one of the ditches had been dredged, which removed fine textured sediments (clay = 41%) with high organic matter content (85 g/kg) and exposed coarse textured sediments (clay = 15%) with low organic matter content (2.2 g/kg). Sediments were subjected to a three-phase experiment (equilibrium, uptake, and release) in recirculating 10-m-long, 0.2-m-wide, and 5-cm-deep flumes to evaluate their role as sources and sinks of P. Under conditions of low initial P concentrations in flume water, sediments from the dredged ditch released 13 times less P to the water than did sediments from the ditch that had not been dredged, equivalent to 24 mg dissolved P. However, the sediments from the dredged ditch removed 19% less P (76 mg) from the flume water when it was spiked with dissolved P to approximate long-term runoff concentrations. Irradiation of sediments to destroy microorganisms revealed that biological processes accounted for up to 30% of P uptake in the coarse textured sediments of the dredged ditch and 18% in the fine textured sediments of the undredged ditch. Results indicate that dredging of coastal plain drainage ditches can potentially impact the P buffering capacity of ditches draining agricultural soils with a high potential for P runoff.

(KEY TERMS: nonpoint source pollution; nutrients; transport and fate; water conservation.)

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INTRODUCTION

Eutrophication is the most common impairment of surface water in the United States (U.S. Geological Survey, 1999), and is exacerbated by phosphorus (P) runoff from agricultural land (Carpenter *et al.*, 1998). In areas of poor soil drainage, open ditches can serve as important conduits of nutrients, with P as a particular concern in areas where livestock manures are applied to field soils (Sharpley *et al.*, 2007). For instance, drainage ditches of the Delmarva Peninsula's poultry producing region have been reported to export more than 20 kg/ha of total P in a single year from fields receiving poultry litter (Needelman *et al.*, 2007). Although ditches are primarily designed to route excess water from agricultural field soils, they can have a profound effect on chemical and biological processes that control nutrient mobility to the water bodies (Needelman *et al.*, 2007). Thus, successful management of P loss from ditch-drained soils require consideration of not only field management practices but also the role of drainage ditch management on P transport and transformations (Sharpley *et al.*, 2007).

Various ditch management practices have the potential to affect P transport in drainage ditches, including controlled drainage, sediment removal, and vegetated buffers, with the effects of some practices better understood than others (Needelman *et al.*, 2007). Controlled drainage (use of coffer dams to raise water tables during critical periods of flow) and vegetated buffers have been identified as best management practices for nutrient conservation, and considerable data exist on their effects on water flow and nutrient losses (Cooper *et al.*, 2004; Strock *et al.*, 2007). A more common ditch management practice, but one that has received considerably less attention from the standpoint of nutrient management, is dredging.

Dredging is performed periodically, but routinely, in drainage ditches to increase the flow of water in a ditch and ensure adequate capacity for drainage. On the Delmarva Peninsula, most ditches are dredged on a 10- to 30-year cycle (Public Drainage Task Force, 2000). The excavated materials are generally deposited on ditch banks and in adjacent fields where they may be susceptible to erosion by runoff (Needelman *et al.*, 2006). Dredging also removes biomass (standing as well as that associated with sediments), and newly uncovered sediments typically contain different abundances, diversity, and species composition of organisms than the removed sediments (Koel and Stevenson, 2002). In addition, dredging exposes mineral sediments that most likely have different nutrient buffer capacities than the sediment that was removed.

To date, research on the effect of dredging on P transport in drainage ditches has been limited to several studies from Indiana, limited by geographic scope and even conflicting findings. Smith *et al.* (2006) conducted flume experiments with sediments representing conditions before and after dredging to evaluate P sorption of enriched ditch water followed by desorption to clean ditch flow. They found that dissolved P removal from water representing P-enriched conditions was greater for sediments removed by dredging than it was for the new sediments exposed after dredging. When the flume waters were replaced with deionized water, the sediments representing post-dredging conditions released more dissolved P to the water column than did the sediments representing predredging conditions. Thus, dredging appeared to reduce the capacity of ditches to buffer P losses from agricultural catchments. Later findings by Douglas Smith (2007, personal communication), however, indicate that the long-term (seasonal or annual) impacts of dredging may not be quite as detrimental to water quality as those expected immediately after dredging.

A mechanistic understanding of the role of dredging on P fate within drainage ditches requires consideration of abiotic and biotic processes. The abiotic exchange of P between the water column and suspended and/or bottom sediments is widely considered as a dominant component of the P cycle in fluvial systems (McCallister and Logan, 1978; Klotz, 1985). Exchange processes that affect the ability of a stream to temporarily retain and regulate dissolved P concentrations are governed by geochemical factors such as pH, oxidation and reduction, organic matter content, electrolyte composition, and sediment composition (mineralogy and texture) (Syers *et al.*, 1973; Klotz, 1985; Stone and English, 1993). Also, P retention can vary within stream reaches depending on stream morphology and vegetation (Munn and Meyer, 1990). For instance, finer sediments found in pools have been found to have a higher retention capacity for dissolved P than coarser sediments in riffles (Munn and Meyer, 1990).

Several studies have cited microbial processes to be important to P dynamics in fluvial systems (Horne and Goldman, 1994; Barko and James, 1998; Haggard *et al.*, 1999). For instance, immobilization of dissolved forms of P by sediment-associated microbes can significantly enhance the ability of a stream to buffer P inputs (Haggard *et al.*, 1999). Sharpley *et al.* (2006), evaluating the effect of physical, chemical, and biological properties of ditch sediments collected from forested and agricultural areas of a single farm, found that microbial P biomass accounted for 25-40% of P uptake. However, the proportion of P in the microbial biomass can fluctuate in response to environmental changes, including redox conditions and

water and nutrient availability (Gachter and Meyer, 1993). Elsewhere, Sallade and Sims (1997) observed that the equilibrium P concentration at zero sorption (EPC_0) of ditch sediments overestimated dissolved P concentrations in winter ditch water samples and underestimated concentrations in summer ditch water samples, hypothesizing that these discrepancies reflected changes in P solubility of ditch soils with seasonal cycles of biological immobilization/mineralization and oxidation/reduction.

Given the importance of drainage ditches to P export from agricultural lands on the Delmarva Peninsula, as well as the paucity of information on the effects of dredging drainage ditches on P transport processes, we sought to evaluate the effect of dredging on P transport from ditches draining P-enriched agricultural soils through a series of flume experiments. Specifically, ditch sediments, representing conditions before and after ditch dredging, were exposed to a series of treatments in a recirculating flume to assess their capacity to serve as a source or sink of dissolved P in flowing water. As part of these experiments, we sought to isolate the effects of dredging on abiotic and biotic processes.

MATERIAL AND METHODS

Site Description

Two drainage ditches were identified on the research farm at the University of Maryland Eastern Shore (UMES), Princess Anne, Maryland, within the 24,000-ha Manokin River Watershed. Prior to its purchase by UMES in 1997, the farm had been a commercial broiler operation for nearly 30 years. Mean annual rainfall in Princess Anne is 1,110 mm and mean temperature is 13°C (U.S. Department of Agriculture–Natural Resources Conservation Service, 2006).

Soils on the UMES farm belong primarily to the poorly drained Othello series (fine-silt, mixed, active, mesic Typic Endoaquult), which are derived from silt eolian sediments underlain by coarser marine sediments (Matthews and Hall, 1966). Due to its long history as a poultry operation, the farm's soils have Mehlich-3 P concentrations as high as 450 mg/kg in the surface horizons and 80 mg/kg in subsurface horizons at 1-m depth.

Soils on this farm are extensively ditched, with shallow field ditches (<1.5 m) maintained by the farm operator draining to deeper collection ditches (>2 m) that are managed by a public drainage association. The drainage ditches used for this study

belong to the field ditch category (1.0 m deep \times 280–300 m long) and are described as Ditches 1 and 2 by Kleinman *et al.* (2007). These ditches have a combined contributing area of approximately 4.5 ha, and drain fields that are in an annual rotation of corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.). Kleinman *et al.* (2007) estimated that surface runoff contributed only 3–9% of the flow in Ditches 1 and 2, indicating that more than 90% of ditch flow derives from ground water. Prior to dredging, ground-water wells monitored over a two-year period had average dissolved P concentration of 0.02 mg/l at depths corresponding with the bottom of the ditch (1.3 m). However, this concentration does not represent storm flow conditions when most P is transport in ditch flow.

Ditch 1 (Figure 1A) was dredged in July 2006, shortly before sediment sampling, while Ditch 2 (Figure 1B) remained undredged. Dredging was conducted by using a backhoe and laser level, engineered to provide a 0.2% slope while removing approximately 0.5 m of bed material. Dredged material was hauled off-site so that it would not serve as a potential source of nutrients and sediment to field runoff and ditch water flow.

Sediment Sampling and Irradiation

Sediment sampling was conducted in October 2006, shortly after the dredging of Ditch 1. At the time of the sediment collection, vegetative cover was removed before sampling (vegetation had not yet become established in Ditch 1). Bulk samples of the upper 5 cm of sediment were collected, placed into 110 l sealed plastic containers, mixed thoroughly, and stored at 4°C.

To test the effects of sediment microbial processes on P fate, half of the sediment sample from each ditch was irradiated at a dose of 5 Megarads (Sterigenics International, Inc., Oak Brook, Illinois). The gamma radiation is a form of pure energy, emitted from Cobalt-60, similar in many ways to microwaves and X-rays. This irradiation is generally characterized by its deep penetration and low doses rates, and effectively kills microorganisms by attacking the DNA molecule.

Three-Phase Flume Experiment

A flume (a stream simulator), previously described by McDowell and Sharpley (2003), was used to evaluate sediment controls of dissolved P transport in simulated ditch flow. Two replicates of each ditch sediment (dredged and undredged) were placed into



FIGURE 1. Experimental Sites in the UMES Research Farm. Site (A) dredged drainage ditch, site (B) undredged drainage ditch.

separate, 10-m \times 20-cm flumes to a depth of approximately 5 cm. The flumes were set at a slope of 0.7%. The reservoir of each flume was filled with 200 l of water. Water was pumped onto the sediment at 0.17 l/s (the mean base flow of the two ditches) at the uphill end of the flume and reentered the reservoir at the downhill end of the flume.

The experiment involved three phases, each lasting 48-hour, as follows:

1. an initial “Equilibration” phase in which sediments were exposed to deionized water to assess initial P desorption;
2. an “Uptake” phase in which water from the Equilibration phase (Phase 1) was first removed and the sediments were then exposed to simulated runoff water to assess P uptake by the sediments; and
3. a final “Release” phase in which the water from the Uptake phase (Phase 2) was removed and sediments were again exposed to deionized water to assess their potential to retain the P from the Uptake phase.

For the Uptake phase (Phase 2), water that equilibrated in the flumes during the Equilibration phase (Phase 1) was replaced with 200 l of water enriched with P (2.5 mg/l) from poultry litter to represent surface runoff input from surrounding agricultural fields (Kleinman *et al.*, 2007). This simulated runoff water was created by steeping poultry litter from the UMES Research Farm in deionized water for 24-hour at 25°C. After 24-hour, the liquor was analyzed for dissolved P and subsequently diluted into 200 l of deionized water to achieve the final desired dissolved P concentration of 2.5 mg/l. Notably, the use of deionized water in the Equilibration and Release phases (Phases 1 and 3) does not precisely simulate the ionic strength of ditch water; however, deionized water is frequently used to quantify the maximum potential for soils or sediments to release P to solution, and trends observed with deionized water and water with weak ionic strength should not be substantially different.

Flume water samples were collected at the downhill end of the flume (just prior to reentry into the reservoir) during all phases (Equilibration, Uptake, and Release) using automated samplers (Model 900; American Sigma, Lakeland, Colorado) at increasing time intervals during each phase: 5 min (0-15 min), 15 min (30-60 min), 30 min (90-120 min), 1 hour (3-6 h), 2 hour (8-16 h), and 4 hour (20-48 hour). Samples were removed from the auto-sampler daily, immediately filtered (0.45 μ m), and stored at 4°C prior to laboratory analysis.

Both nonirradiated and irradiated sediments were subjected to the Equilibration phase (Phase 1). During the Uptake phase (Phase 2) of the experiment with irradiated sediments, apparently sediments had become colonized by microbes. Because the intent of testing irradiated sediments had been precluded, which was to assess the role of microbial processes in P cycling, only nonirradiated sediments were

subjected to the final two phases of the flume experiments.

Laboratory Analyses

Sediment Characterization. Sediments representing initial conditions as well as conditions at the end of each experimental phase were analyzed for Mehlich-3 P (Mehlich, 1984) and water extractable P (WEP). Mehlich-3 P was analyzed by shaking 1 g of sediment with 10 ml of Mehlich-3 P solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M HNO_3 + 0.001 M EDTA) for 5 min. WEP was determined using the method of Vaughan *et al.* (2007b) by shaking 1 g of soil in 10 ml of deionized water for one hour. The supernatant was filtered (Whatman #1) and extracts analyzed colorimetrically (Murphy and Riley, 1962). Ammonium oxalate extractable P, Al, and Fe were extracted from sediments by shaking 0.5 g of sediment with 20 ml 0.1 M $(\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}$ + 0.1 M $\text{H}_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ (pH adjusted to 3.0) in the dark for 4 hour (McKeague and Day, 1966). Extractable Al, Fe, and P (Al_{ox} , Fe_{ox} , P_{ox}) were determined in the supernatant by inductively coupled plasma optical emission spectroscopy.

Total P in the sediments was measured by modified semi-micro Kjeldahl procedure (Bremner, 1996), with P determined by the method of Murphy and Riley (1962) at $\lambda = 712$ nm. Particle size distribution of sediments was determined by hydrometer method (Day, 1965). Organic matter was determined by the loss on ignition method (360°C), and pH was determined in water (1:1).

Phosphorus sorption isotherms for irradiated and nonirradiated sediments were generated by shaking 1 g of sediment with various additions of P (0-1,000 mg/kg added as KH_2PO_4) in 25 ml of 0.01 M CaCl_2 on an end-over-end shaker at 24°C (Nair *et al.*, 1984). After 24 hour, sediment suspensions were centrifuged and filtered (Whatman #1), filtrate P concentration was determined by the colorimetric method of Murphy and Riley (1962).

Flume Water Analysis. Water samples were analyzed for dissolved P via phosphomolybdate reduction using Lachat QuickChem Method 10-115-01-1-A (Diamond, 1995).

Batch Sediment Uptake and Release Evaluations. To elucidate abiotic and biotic processes affecting sediment P dynamics, sequential P uptake and release experiments were conducted. Fresh sediments were incubated in the laboratory (25°C) with a series of solutions at a sediment:solution ratio of 1 g:2.5 ml, which was identical to the sedi-

ment:solution ratio of the flume experiments. Sediment samples representing conditions at the start of the flume study were first subjected to a 24-hour period of P uptake in a solution of 2.5 mg P/l (as KH_2PO_4). This step was used to simulate the P Uptake phase of the flume experiments. Samples were then centrifuged and the solution and solid phases separated by filtration (Whatman #1). Solution P was analyzed by colorimetry. Sediment samples were then subjected to a 24-hour release period using 0.01 M CaCl_2 solution. This step simulated the P Release phase of the flume experiments. Solid solution separation by filtration and solution P determination steps were repeated. Following this step, a subset of the samples was irradiated, as described above. Irradiated sediment samples and nonirradiated sediment samples were then subjected to a final 24-hour period of P release in 0.01 M CaCl_2 solution, and the same procedure described above was used to determine dissolved P. The role of biotic processes in P uptake was calculated by the difference in dissolved P obtained from irradiated and nonirradiated sediments for this final release phase. All treatments were conducted in duplicate.

Data Analysis

Phosphorus sorption properties of the sediments were estimated from the isotherm data using a Langmuir model. The P sorption maximum (S_{max} ; mg/kg) was calculated as the reciprocal of the slope of the plot C/S vs. C , where C is dissolved P concentration in solution and S is the concentration of P sorbed by the sediment. The binding energy (l/kg) was estimated by dividing the slope of the same relationship by the y -intercept (Olsen and Watanabe, 1957; Syers *et al.*, 1973). The initial slope of a graph of P sorbed (mg/kg) against P remaining in solution (mg/l) was used to estimate equilibrium P concentration (EPC_0 ; mg/l) as the solution P concentration at which no net sorption or desorption occurred (0 mg/kg). The degree of P saturation (DPS) of the sediments was estimated as

$$\text{DPS (\%)} = (\text{P}_{\text{ox}} / \text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}) \times 100, \quad (1)$$

where Al_{ox} , Fe_{ox} , and P_{ox} are in mmol/kg (Breeuwsma and Silva, 1992).

Dissolved P concentrations and time after initiation of the flume experiments were modeled using a power function

$$C = \alpha t^\beta, \quad (2)$$

where t is the time after the onset of flow (minutes), α estimates the y intercept, and β quantifies the rate of change in P concentrations. Power equations were fitted by regression techniques in SPSS v.10.0 (SPSS, 1999) and a coefficient of determination estimated from the linear relationship of observed and predicted values.

Plateau analyses were conducted on temporal trends in dissolved P by split regressions (quadratic-linear) as part of the NLIN routine in SAS v. 8 (SAS Institute Inc, 1999). Analysis of variance, Tukey's mean separation, and Student's t -test were performed in Minitab v. 15 (Minitab Inc., 2001). Results discussed in the text were considered significant at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Initial Properties of Ditch Sediments

Prior to the dredging of Ditch 1, the two ditches were believed to have undergone similar management histories, such that the ditch sediments had similar properties before dredging (Vaughan *et al.*, 2007b). Fields surrounding the two ditches were managed similarly, as reflected by similar Mehlich-3 P (421-447 mg/kg) and DPS (66-78%) values of field soils (Kleinman *et al.*, 2007). From 2001 to 2006, mean annual flow from the ditches ranged from 3,308 m³ (2001-2002) to 17,999 m³ (2004-2005) with differences primarily reflecting variability in annual rainfall (762 mm during 2001-2002 period and 1,371 mm during 2004-2005 period). Mean annual losses of P from the ditches ranged from 1.4 kg total P/ha (2001-2002) to 26.2 kg total P/ha (2003-2004).

Dredging Ditch 1 exposed sediments that differed dramatically from those in the undredged ditch

(Table 1). Dredging removed sediments high in organic matter (85 g/kg) with fine particles (19% sand, 41% clay) and exposed sediments of coarse texture (68% sand, 15% clay) with low organic matter content (2.2 g/kg). These differences coincided with substantially lower P sorption capacities in the sediments exposed by dredging, as reflected by oxalate extractable Al and Fe, which were roughly five to 11 times lower, respectively, than concentrations in the sediments from the undredged ditch (Table 1). Notably, the pH of all sediments was <5.0, although the lowest pH values were observed in the sediments from the undredged ditches that had higher concentrations of Al and Fe, and likely had higher concentrations of organic acids (Vaughan *et al.*, 2007a).

Higher concentrations of P were observed in sediment from the undredged ditch (Table 1), likely representing the accumulation of P from surface and near-surface flow over time, as well as the deposition of P-enriched sediments and organic matter (Vaughan *et al.*, 2007b). Undredged ditch sediments had higher EPC₀ and DPS, but due to their higher Al_{ox} and Fe_{ox} content, had a higher S_{max} (Table 1).

Three-Phase Flume Experiment – Nonirradiated Sediments

Phase 1: Phosphorus Equilibration. Sediments equilibrated rapidly with deionized water in the flumes. For the sediments from the dredged ditch, the concentration of dissolved P in the flume water increased within the first 5 min and remained constant (mean = 0.01 mg/l) for the duration of the phase. For the sediments from the undredged ditch, dissolved P concentrations increased over the initial 140 min before plateauing at a mean concentration of 0.13 mg/l (Fig. 2A). During the Equilibration phase, differences in dissolved P concentrations between the two sediments resulted in significantly more P being

TABLE 1. Physical and Chemical Properties of Undredged and Dredged Ditch Sediments Before and After Irradiation.

Oxalate																
Sediments	M3P	WEP	Total P	P	Al	Fe	Sorption Maximum	EPC ₀	DPS	Binding Energy	pH	OM	Sand	Silt	Clay	
					mg/kg			mg/l	%	l/kg		g/kg		%		
Nonirradiated																
Dredged	53	0.5	146	80	246	484	187	0.03	15	0.366	4.9	2.2	68	17	15	
Undredged	117	1.2	1,002	1,073	1,266	5,328	459	0.12	24	0.454	4.2	85	19	34	41	
Irradiated																
Dredged	66	0.45	90	96	283	501	159	0.04	16	NA	5.4	2.2	68	17	15	
Undredged	159	2.67	1,038	1,294	1,550	5,896	455	0.13	26	NA	4.4	98	19	34	41	

Note: EPC₀, equilibrium phosphorus concentration; DPS, degree of P saturation; M3-P, Mehlich-3 extractable soil P; OM, organic matter; WEP, water extractable P.

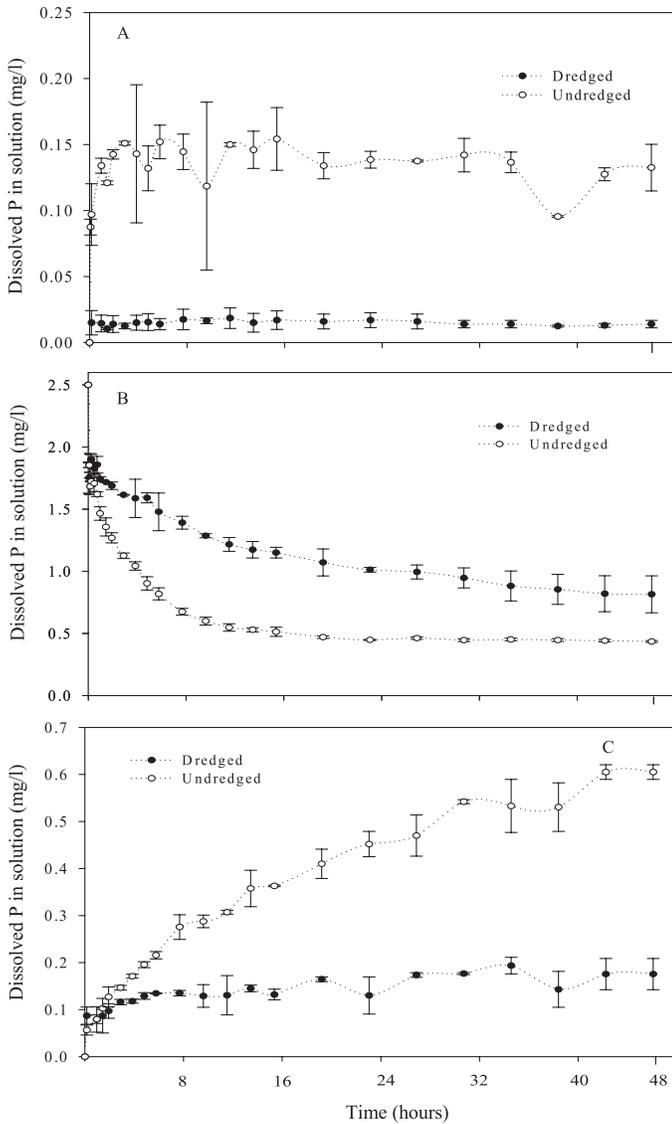


FIGURE 2. Three-Phase Experiment. Phosphorus equilibration phase (A), uptake phase (B), and release phase (C) over 48 hours for nonirradiated ditch dredged sediments.

released from sediments of the undredged ditch (26 mg P) than from those of the dredged ditch (2 mg P). Relative differences in dissolved P concentrations related well to the initial EPC_0 values of the dredged ditch (0.03 mg/l) and undredged ditch (0.12 mg/l) sediments, and corresponded roughly with differences in the various P pools (Table 1), consistent with P release findings from other flume experiments that evaluated sediments with contrasting properties (e.g., Smith *et al.*, 2006; Sharpley *et al.*, 2007). As such, dredging the fine textured, P-rich sediment would appear to substantiate the lower potential for ditch sediments to serve as a source of dissolved P to ditch flow, at least when dissolved P concentrations are low in the remaining ditch sediments.

Phase 2: Phosphorus Uptake. The addition of simulated runoff water (2.5 mg/l dissolved P) to flumes resulted in significant removal of dissolved P from the recirculating water, with a different magnitude in P uptake observed between the two sediments (Figure 2B). Despite their higher initial P content and EPC_0 , sediments obtained from the undredged ditch removed 420 mg of added P, equilibrating after 14-hour at a mean dissolved P concentration of 0.4 mg/l (equivalent to 83% removal of dissolved P from simulated runoff water). In contrast, the sediments from the dredged ditch removed a total of 338 mg P from the flume water, with dissolved P concentrations continuing to decline during 36-hour before reaching a final concentration of 0.81 mg P/l (equivalent to 68% removal of dissolved P from simulated runoff water).

The quantity of dissolved P uptake by sediments reflects differences in their sorption properties, with concentrations at the end of the 48-hour recirculation period consistent with the S_{max} of the two sediments (Table 1). As described above, the greater concentrations of oxalate extractable Fe and Al in the undredged ditch sediments point to a greater P sorption capacity. Removal of reactive Fe and Al in sediments by dredging decreased the capacity to remove added P in ditch flow. Notably, the kinetics of P uptake also appeared to be related to P sorption properties. When the relationship of dissolved P concentration in runoff and time were described by a power function, the decay rate ($\beta = -0.18$ for dredged ditch sediments and $\beta = -0.33$ for undredged ditch sediments) and Langmuir binding energy (0.366 l/kg for dredged ditch sediments and 0.454 l/kg for undredged ditch sediments) were proportional (Tables 1 and 2).

Results of the Uptake phase corroborate earlier results from the literature. Meyer (1979), conducting a batch experiment to evaluate P sorption by sediments ranging from course sands with low organic matter content (1%) to silts with high organic matter content (8%), reported that the silt sediments removed 93% of dissolved P from solution within 5 min, whereas the sandy sediments removed only 19% of dissolved P from solution during the same period. In a flume experiment similar to that of the current study, Smith *et al.* (2006) found that before

TABLE 2. Kinetic Parameters From P Uptake and Release Experiments With Nonirradiated Sediments.

Sediments	Uptake			Release		
	α	β	r^2	α	β	r^2
Dredged	3.6867	-0.1753	0.89	0.047	0.1663	0.87
Undredged	5.3098	-0.3256	0.96	0.0134	0.4792	0.99

dredging, P sorption by ditch sediments was more rapid and equilibrated at a lower concentration than sediments exposed by dredging. Our study also found that P sorption was related to the reactive Fe and Al concentration of sediments.

Our findings highlight the potential importance of ditch sediments in buffering field losses of P in runoff and contrast with initial inferences drawn from the Equilibration phase of the flume experiment. Sediments exposed by dredging had properties that substantially lowered their ability to remove P from flowing water. As most P in flow from the two ditches occurs during periods of runoff (5-year average was 60%, ranging from 47 to 75%), the initial concentrations used in this phase are representative of those observed under natural conditions (Kleinman *et al.*, 2007). In this scenario, results of the Uptake phase point to dredging as decreasing the potential for ditches to buffer field losses of P. The slower uptake rate by sediments after dredging suggests that the impact of dredging on P transport under field conditions could be substantially greater than the impact observed in a recirculating flume. In other settings, however, a different stratification of sediments of varying properties may occur (e.g., P sorption potential often increases through the profile of upland soils). Thus, these results should be interpreted in the context of an Atlantic Coastal Plain setting where fine textured surface materials with relatively high P sorption overlie coarse textured materials of low P sorption potential.

Phase 3: Phosphorus Release Following Uptake. A large amount of P removed from the water column during the Uptake phase was released back to the deionized water introduced into the flumes at the beginning of the Release phase (Figure 2C). A total of 10% (dredged) and 30% (undredged) of P taken up in the previous phase was released back to the water column from sediment. Release of P from undredged ditch sediments contin-

ued through the 48-hour period with a final concentration of 0.60 mg/l. For sediments from the dredged ditch, P release occurred primarily during the initial 10-hour, after which dissolved P concentrations remained static at 0.17 mg/l. These findings suggest that recently adsorbed P in sediment from the undredged ditch is more labile than P in the dredged ditch sediment, and are consistent with the differences in WEP concentrations of sediment samples obtained at the end of the Release phase (Table 3). It is likely that the extremely high DPS of the undredged sediments (24%), well above environmental thresholds for soils reported elsewhere in the literature (e.g., Kleinman *et al.*, 2000; Maguire and Sims, 2002), contributed to the poor retention of P from the Uptake phase. It is important to note that DPS calculated by other studies sometimes include an α coefficient to modify the P sorption capacity portion of this equation, whereas we do not. In studies employing the common α of 0.5, DPS values would be twice those estimated in the current study.

Findings of this study differ markedly from those obtained in several other recent flume studies of sediment controls on P transport. Smith *et al.* (2006), who evaluated ditch sediments representing conditions before and after dredging, reported significantly greater concentrations of dissolved P in flumes with sediments obtained after dredging, despite lower removal of dissolved P in the Uptake phase by these same sediments. They concluded that the sediments exposed to ditch flow prior to dredging converted dissolved P into more stable complexes than sediments after dredging. Elsewhere, McDowell and Sharpley (2003) found that fluvial sediments that removed most dissolved P from the water column during periods of relatively high dissolved P concentration in flow, released less dissolved P at a later point when concentrations in the water column were lower. As protocols in the studies of Smith *et al.* (2006) and McDowell and Sharpley (2003) were similar to those employed by the current study, the sediment

TABLE 3. Mehlich-3 P and Water Extractable P Concentrations of Nonirradiated and Irradiated Sediments for Each Phase of the Flume Experiment.

Phases	Dredged		Undredged		Dredged		Undredged	
	Nonirradiated				Irradiated			
	WEP	M3P	WEP	M3P	WEP	M3P	WEP	M3P
	mg/kg							
End of Equilibrium phase	0.77 (0.04)	76 (6.67)	1.4 (0.27)	113 (3.49)	0.58 (0.00)	73 (10.12)	2.71 (0.03)	143 (13.06)
End of Uptake phase	0.79 (0.08)	75 (8.14)	1.9 (0.15)	135 (10.41)	NA	NA	NA	NA
End of Release phase	0.60 (0.07)	62 (0.27)	1.6 (0.04)	120 (5.20)	NA	NA	NA	NA

Note: M3-P, Mehlich-3 extractable soil P; WEP, water extractable P; NA, not available.

properties might account for the discordant findings. For instance, the DPS and EPC_0 of the sediments evaluated by Smith *et al.* (2006) were greater following dredging than before dredging, whereas the DPS and EPC_0 of sediments in the current study were lower in sediments following dredging.

Results of the Release phase demonstrate the dynamic nature of sediment interactions with flowing water and potential for variable roles of sediments as sinks or sources of P to ditch flow. Under one set of conditions, sediments served as relatively large sinks of P, while under another set of conditions they served as substantial sources of P to water. Even so, when one sums the mass of P measured in the flume water at the end of each phase of the flume experiment, the accumulated mass of P remaining in flume water was similar for the two sediments, totaling 243 mg for the dredged ditch sediments and 235 mg for the undredged ditch sediments. Although these absolute values are largely a function of the protocol of the current experiment (e.g., dissolved P concentration, recirculation of flow, duration of experimental phase), they help place the large losses observed in the Release phase into context. Dredging ultimately resulted in a 4% increase in P retained in flow across the three phases of the flume experiment.

Biological Processes Affecting Phosphorus Uptake and Release. Biological processes appeared to affect both P release and uptake characteristics of the sediments, with laboratory experiments yielding more definitive insight into these processes than the flume experiments. In the flume experiment, concentrations of dissolved P in the water column varied widely for the irradiated sediments, particularly for flumes packed with the undredged ditch sediments (Figures 2 and 3). The possibility exists that soil microorganisms colonized the sediments of the open flumes during the experiments, which spanned several days and warrants caution in interpreting these results. As a result, conclusions regarding biological processes are derived primarily from the laboratory batch experiments and sediment extractions.

Phosphorus Equilibration of Irradiated Sediments

Results of P Equilibration experiments indicate that there was a substantial amount of microbial P in the ditch sediments. Irradiation of the undredged sediments resulted in the release of P from lysed cells as indicated by the increases observed in sediment WEP, Mehlich-3, P, and EPC_0 (Table 1). In the flume experiments, irradiated sediments released 10% more dissolved P to the flume water than did nonirradiated sediments (Fig. 3). Elsewhere, Eno and Popenoe

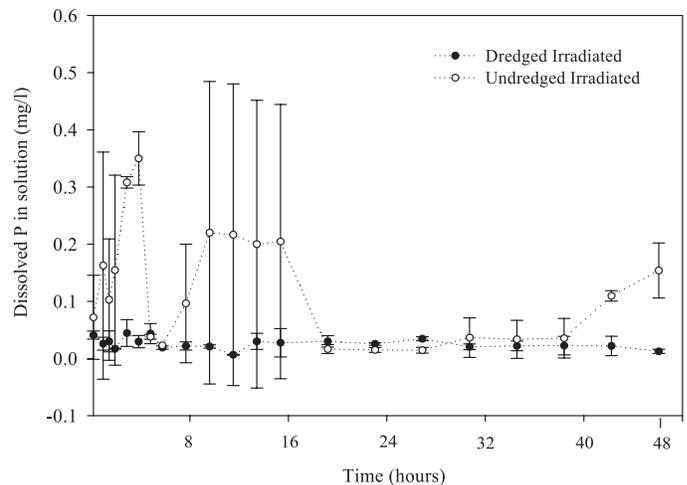


FIGURE 3. Phosphorus Equilibration Phase for Irradiated Ditch Dredged and Undredged Sediments.

(1963) concluded that gamma irradiated treated sediments released more P as a result of cell lysis and disruption of sediment organic matter.

Irradiation appeared to have a larger effect on dissolved P release from sediment of the undredged ditch during the Equilibration phase, pointing to larger pools of microbial P in these finer textured sediments with high organic matter content than in the sediments of the dredged ditch. In the flume experiments, dissolved P release was equivalent to 0.025 mg/kg microbial P in the dredged ditch sediment and 0.05 mg/kg microbial P in the undredged ditch sediment. Irradiation resulted in greater increases in WEP of sediment from the undredged ditch than in sediment from the dredged ditch (Table 3).

Role of Microorganisms in Phosphorus Uptake

Laboratory simulation of the P Uptake phase (batch experiment starting with a P-enriched solution of 2.5 mg/l) resulted in trends by nonirradiated sediments that roughly followed those observed in the flume experiments already described. Sediments from the dredged ditch removed little dissolved P from the enriched P solution (2.6%), whereas sediments from the undredged ditch removed 24% of P from solution (Figure 4A). An initial release phase of nonirradiated sediments resulted in a return to solution of 75 and 83% of the P removed in the uptake phase by sediments from the dredged and undredged ditches, respectively (Figure 4B). Subsequent irradiation of sediments to release P immobilized during the Uptake phase resulted in 30 and 18% differences in P release between irradiated and nonirradiated sediments of dredged and undredged ditches, respectively (Figure 4C). Although these results were not

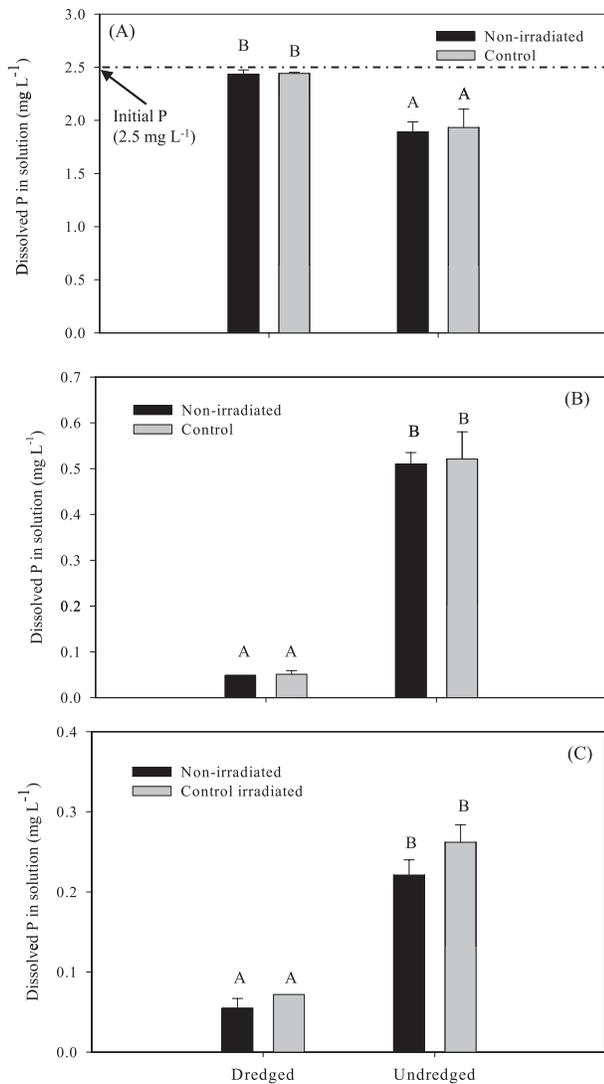


FIGURE 4. Batch Experiment. Dissolved phosphorus concentrations at end of simulated uptake (A), first release (B), and second release irradiated (C) phases in laboratory study. Letters above columns indicate Tukey's mean groupings.

statistically significant, they are consistent with estimates in the literature of microbial contributions to P uptake. McDowell and Sharpley (2003) estimated that 30% of dissolved P uptake by fluvial sediments occurred as a result of microbial immobilization. Sharpley *et al.* (2007) observed a microbial contribution on P uptake of 22 and 42% for forest and agricultural ditch sediments, respectively.

CONCLUSIONS

Data from this study show that for the short duration considered here, the potential for P transport in

drainage ditches is influenced by dredging. Removal of P-saturated sediments with a high EPC_0 via dredging can decrease P release to flowing water by exposing sediments with a lower EPC_0 ; however, such benefits can only be expected to occur when background concentrations of dissolved P in ditch flow are regularly below the EPC_0 of the sediments that were removed by dredging.

In areas such as the major livestock producing areas of the Atlantic Coastal Plain, high concentrations of dissolved P are routinely derived from sources other than sediments (field soils, applied manures, point sources) (Sallade and Sims, 1997; Kleinman *et al.*, 2007). In such cases, dredging can significantly decrease the potential for sediments to buffer dissolved P losses in ditch flow. Dredging removes P sorbing materials as well as microbial populations that can contribute substantially to dissolved P uptake. In the current study, sorption of dissolved P by mineral species (esp. sesquioxides) likely accounted for 70-82% of P uptake by sediments. Recognizing the role of drainage ditches as a P sink is vital to management of current farming systems. However, ditches cannot be viewed as permanent P sinks. Much of the P stored by ditch sediments is highly labile, as demonstrated by the P Release phase of the flume experiments.

Ultimately, the development of sustainable ditch-drained farming systems requires the control of P sources to and within ditches. While the current study offers insight into the effects of dredging on the fate of dissolved P in ditches, other aspects of dredging, such as the fate of dredged sediments that are simply dumped on ditch walls or on adjacent field soils, may play an equal or more important role in the fate of P. Prudent management of drainage ditches requires weighing the adverse impacts of dredging with intended benefits.

DISCLAIMER

Mention of trade names does not imply endorsement by the U.S. Department of Agriculture.

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LITERATURE CITED

- Barko, J.W. and W.F. James, 1998. Effects of Submerged Aquatic Macrophytes on Nutrient Dynamics, Sedimentation, and Resuspension. *In: The Structuring Role of Submerged Macrophytes in Lakes*, E. Jeppeson, M. Sondegaard, and K. Christofferson (Editors). Springer, New York, New York, pp. 197-214.
- Breeuwsma, A. and S. Silva, 1992. Phosphorus Fertilization and Environmental Effects in the Netherlands and the Po Region (Italy). Agric. Res. Dep. Rep. 57. Winand Staring Centre for Integrated Land, Soil and Water Res., Wageningen, The Netherlands.
- Bremner, J.A., 1996. Nitrogen – Total. *In: Methods of Soils Analysis. Part. 3. Chemical Methods*, D.L. Sparks (Editor). SSSA Book Series n. 5. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin, pp. 1085-1121.
- Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith, 1998. Nonpoint Pollution of Surface Waters With Phosphorus and Nitrogen. *Ecological Applications Journal* 8:559-568.
- Cooper, C.M., M.T. Moore, E.R. Bennett, S. Smith, Jr., J.L. Farris, C.D. Milam, and F.D. Shields, Jr., 2004. Innovative Uses of Vegetated Drainage Ditches for Reducing Agricultural Runoff. *Water Science and Technology* 49:117-123.
- Day, P.R. 1965. Particle Fractionation and Particle Size Analysis. *In: Methods of Soil Analysis, Part 1.*, C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark (Editors). Agronomy Monograph 9:545-567. American Society of Agronomy, Madison, Wisconsin.
- Diamond, D. 1995. Determination of Orthophosphate in Water by Flow Injection Analysis Colorimetry. Lachat Instruments, Milwaukee, Wisconsin.
- Eno, C.F. and H. Popenoe, 1963. The Effect of Gamma Radiation on the Availability of Nitrogen and Phosphorus. *Soil Science Society of America Journal* 27:299-301.
- Gachter, R. and J.S. Meyer, 1993. The Role of Micro-Organisms in Mobilization and Fixation of Phosphorus in Sediments. *Hydrobiologia* 253:103-121.
- Haggard, B.E., E.H. Stanley, and R. Hylar, 1999. Sediment-Phosphorus Relationships in Three Northcentral Oklahoma Streams. *Transactions of American Society of Agricultural Engineering* 42:1709-1714.
- Horne, A.J. and C.R. Goldman, 1994. *Limnology (Second Edition)*. McGraw-Hill, New York, New York.
- Kleinman, P.J.A., A.L. Allen, B.A. Needelman, A.N. Sharpley, P.A. Vadas, L.S. Saporito, G.J. Folmar, and R.B. Bryant, 2007. Dynamics of Phosphorus Transfers From Heavily Manured Coastal Plain Soils to Drainage Ditches. *Journal of Soil and Water Conservation* 62(4):225-234.
- Kleinman, P.J.A., R.B. Bryant, W.S. Reid, A.N. Sharpley, and D. Pimentel, 2000. Using Soil Phosphorus Behavior to Identify Environmental Thresholds. *Soil Science* 165:943-950.
- Klotz, R.L., 1985. Factors Controlling Phosphorus Limitation in Stream Sediments. *Limnology and Oceanography* 30:543-553.
- Koel, T.M. and K.E. Stevenson, 2002. Effects of Dredge Material Placement on Benthic Macroinvertebrates of the Illinois River. *Hydrobiology* 474:229-238.
- McCallister, D.L. and T.J. Logan, 1978. Phosphate Adsorption-Desorption Characteristics of Soils and Bottom Sediments in the Maumee River Basin of Ohio. *Journal of Environmental Quality* 7:87-92.
- McDowell, R.W. and A.N. Sharpley, 2003. Uptake and Release of Phosphorus From Overland Flow in a Stream Environment. *Journal of Environmental Quality* 32:937-948.
- McKeague, J.A. and J.H. Day, 1966. Dithionite and Oxalate Extractable Fe and Al as Aids in Differentiating Various Classes of Soils. *Journal of Soil Science* 46:13-22.
- Maguire, R.O. and J.T. Sims, 2002. Soil Testing to Predict Phosphorus Leaching. *Journal of Environmental Quality* 31:1601-1609.
- Matthews, E.D. and R.L. Hall, 1966. *Soil Survey of Somerset County, Maryland*. U.S. Gov. Print. Office, Washington, D.C.
- Mehlich, A., 1984. Mehlich 3 Soil Test Extractant: A Modification of Mehlich 2 Extractant. *Communications in Soil Science and Plant Analysis* 15:1409-1416.
- Meyer, J.L., 1979. The Role of Sediments and Bryophytes in Phosphorus Dynamics in a Headwater Stream Ecosystem. *Limnology and Oceanography* 24:365-375.
- Minitab Inc., 2001. Minitab Statistical Software, Release 13.31. Minitab Inc., State College, Pennsylvania.
- Munn, N.L. and J.L. Meyer, 1990. Habitat Specific Solute Retention in Two Small Streams: An Intersite Comparison. *Ecology* 71:2069-2082.
- Murphy, J. and J.P. Riley, 1962. A Modified Single Solution Method for the Determination of Phosphate in Natural Waters. *Analytica Chimica Acta*. 27:31-36.
- Nair, P.S., T.J. Logan, A.N. Sharpley, L.E. Sommers, M. Tabatabai, and T.L. Yuan, 1984. Interlaboratory Comparison of a Standardized Phosphorus Adsorption Procedure. *Journal of Environmental Quality* 13:591-595.
- Needelman, B., P.J.A. Kleinman, and A.L. Allen, 2006. The Ditch Project. *In: Improved Management of Agricultural Drainage Ditches for Water Quality Protection*, B. Needelman, and S. Will (Editors). Field Tour Guide. The Ditch Project's Field Tour and Symposium. University of Maryland, Princess Anne and College Park, Maryland, pp. 1-45.
- Needelman, B.A., P.J.A. Kleinman, S.S. Jeffrey, S. Strock, and A.L. Allen, 2007. Improved Management of Agricultural Drainage Ditches for Water Quality Protection. *Journal of Soil and Water Conservation* 62:171-178.
- Olsen, S.R. and F.S. Watanabe, 1957. A Method to Determine Phosphorus Adoption Maximum in Soils as Measured by the Langmuir Isotherm. *Journal. Soil Science Society of America Journal* 21:144-149.
- Public Drainage Task Force, 2000. Moving Water: A Report to the Chesapeake Bay Cabinet. Contribution No. 2000, Center for the Environment and Society, Washington College, 60 pp. http://www.dnr.state.md.us/streams/pubs/final_pd_report.pdf, accessed on September 25, 2007.
- Sallade, Y.E. and J.T. Sims, 1997. Phosphorus Transformations in the Sediments of Delaware's Agricultural Drainageways: I. Phosphorus Forms and Sorption. *Journal of Environmental Quality* 26:1571-1579.
- SAS Institute Inc, 1999. SAS OnlineDoc ®, Version 8. SAS Institute Inc., Cary, North Carolina.
- Sharpley, A.N., T. Krogstad, B. Haggard, and F. Shigaki, 2006. The Ditch Project. Managing Natural Processes in Drainage Ditches From Non-Point Source Phosphorus Control. *In: Improved Management of Agricultural Drainage Ditches for Water Quality Protection. The Ditch Project Symposium Agenda and Abstracts*, B. Needelman, and S. Will (Editors). University of Maryland, Princess Anne and College Park, Maryland, 5 pp..
- Sharpley, A.N., T. Krogstad, P.J.A. Kleinman, B.E. Haggard, F. Shigaki, and L. Saporito, 2007. Managing Natural Processes in Drainage Ditches for Non-Point Source Phosphorus Control. *Journal of Soil and Water Conservation* 62(4):197-206.
- Smith, D.R., E.A. Warnemuende, B.E. Haggard, and C. Huang, 2006. Dredging of Drainage Ditches Increases Short-Term Transport of Soluble Phosphorus. *Journal of Environmental Quality* 35:611-616.
- SPSS, 1999. SPSS Base 10.0 User's Guide. SPSS, Chicago, Illinois.
- Stone, M. and M.C. English, 1993. Geochemical Composition, Phosphorus Speciation and Mass Transport of Fine-Grained

- Sediment in Two Lake Erie Tributaries. *Hydrobiologia* 253: 17-29.
- Strock, J.S., C.J. Dell, and J.P. Schmidt, 2007. Managing Natural Processes in Drainage Ditches for Nonpoint Source Nitrogen Control. *Journal of Soil and Water Conservation* 62:188-196.
- Syers, J.K., M.G. Browman, G.W. Smillie, and R.B. Corey, 1973. Phosphate Sorption by Soils Evaluated by the Langmuir Adsorption Equation. *Journal. Soil Science Society of America Journal* 37:358-363.
- U.S. Department of Agriculture–Natural Resources Conservation Service, 2006. National Water and Climate Center. <ftp://ftp.wcc.nrcs.usda.gov/support/climate/wetlands/md/24039.txt>, accessed March 5, 2006.
- U.S. Geological Survey, 1999. The Quality of Our Nation's Waters: Nutrient and Pesticides. Circ. 1225. USGS, Reston, Virginia.
- Vaughan, R.E., B.A. Needelman, P.J. Kleinman, and A.L. Allen, 2007a. Spatial Variation of Soil Phosphorus Within a Drainage Ditch Network. *Journal of Environmental Quality* 36:1096-1104.
- Vaughan, R.E., B.A. Needelman, P.J.A. Kleinman, and A.L. Allen, 2007b. Vertical Distribution of Phosphorus in Agricultural Drainage Ditch Soils. *Journal of Environmental Quality* 36:1895-1903.