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Phosphorus losses from agricultural watersheds in the Mississippi Delta

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ABSTRACT

Phosphorus (P) loss from agricultural fields is of environmental concern because of its potential impact on water quality in streams and lakes. The Mississippi Delta has long been known for its fish productivity and recreational value, but high levels of P in fresh water can lead to algal blooms that have many detrimental effects on natural ecosystems. Algal blooms interfere with recreational and aesthetic water use. However, few studies have evaluated P losses from agricultural watersheds in the Mississippi Delta. To better understand the processes influencing P loss, rainfall, surface runoff, sediment, ortho-P (orthophosphate, PO_4–P), and total P (TP) were measured (water years 1996–2000) for two subwatersheds (UL1 and UL2) of the Deep Hollow Lake Watershed and one subwatershed of the Beasley Lake Watershed (BL3) primarily in cotton production in the Mississippi Delta. Ortho-P concentrations ranged from 0.01 to 1.0 mg/L with a mean of 0.17 mg/L at UL1 (17.0 ha), 0.36 mg/L at UL2 (11.2 ha) and 0.12 mg/L at BL3 (7.2 ha). The TP concentrations ranged from 0.14 to 7.9 mg/L with a mean of 0.96 mg/L at UL1, 1.1 mg/L at UL2 and 1.29 mg/L at BL3. Among the three sites, UL1 and UL2 received P application in October 1998, and BL3 received P applications in the spring of 1998 and 1999. At UL1, ortho-P concentrations were 0.36, 0.25 and 0.16 for the first, second and third rainfall events after P application, respectively; At UL2, ortho-P concentrations were 1.0, 0.66 and 0.65 for the first, second and third rainfall events after P application, respectively; and at BL3, ortho-P concentrations were 0.11, 0.22 and 0.09 for the first, second and third rainfall events after P application, respectively. P fertilizer application did influence P losses, but high P concentrations observed in surface runoff were not always a direct result of P fertilizer application or high rainfall. Application of P in the fall (UL1 and UL2) resulted in more ortho-P losses, likely because high rainfall often occurred in the winter months soon after application. The mean ortho-P concentrations were higher at UL1 and UL2 than those at BL3, although BL3 received more P application during the monitoring period, because P was applied in spring at BL3. However, tillage associated with planting and incorporating applied P in the spring (BL3) may have resulted in more TP loss in sediment, thus the mean TP concentration was the highest at BL3. Ortho-P loss was correlated with surface runoff; and TP loss was correlated with sediment loss. These results indicate that applying P fertilizer in the spring may be recommended to reduce potential ortho-P loss during the fallow winter season; in addition, conservation practices may reduce potential TP loss associated with soil loss.

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1. Introduction

For many years, the prevailing philosophy of soil phosphorus (P) management was to apply P as a fertilizer (whether with inorganic forms or organic forms such as manure) at rates that maintain soil P at or above a critical test level (Thomas and Peaslee, 1973). If a soil P test is not properly calibrated for a specific site or if P fertilizer applications are routinely made above recommended levels, there may be a buildup of soil P in excess of crop needs (Frossard et al., 2000; Higgs et al., 2000; Ma et al., 2009; Messiga et al., 2010; Motavalli and Miles, 2002). A large pool of labile soil P (Larsen, 1967) may increase the quantity of P susceptible to off-site loss with potentially negative impacts on the environment, particularly in fresh water ecosystems (Edwards et al., 2000; Higgs et al., 2000; Smith, 2003; Dodds et al., 2009).

Primary mechanisms for the fate of P added to agricultural soils are utilization by the crop (Martin et al., 1976), retention or fixation within the soil matrix (Sample et al., 1980), and loss in runoff or

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drainage (Sharpley and Syers, 1979; Lennox et al., 1997; Sims et al., 1998; Simard et al., 2000; Quinton et al., 2001; Watson et al., 2007). Phosphorus that has been recently applied as a fertilizer may be relatively soluble or labile and more easily desorbed and subsequently transported by surface and sub-surface flow (Sharpley and Syers, 1979; Lennox et al., 1997; Sims et al., 1998; Quinton et al., 2001). With continuous application of fertilizer P in excess of crop needs, the proportion of labile soil P may increase, resulting in even greater losses of soluble P. Less soluble forms of P bound to soil solids are vulnerable to loss in surface runoff in association with eroded sediment particles transported in overland flow (Seta et al., 1993; Daverede et al., 2003).

Studies have evaluated the processes governing P transport from the sites of fertilizer application (agricultural fields) to water systems (Sharpley, 1995; Quinton et al., 2001; Udawatta et al., 2004; Franklin et al., 2007; Gentry et al., 2007; Little et al., 2007; Udeigwe et al., 2007; Volf et al., 2007; Watson et al., 2007). However, many uncertainties remain with regard to quantifying these processes because of the number of potential influencing factors, including P fertilizer reactions in soil, topography of the landscape (flow pathways from field to water), crop systems, management, and weather patterns.

Regardless of whether the source of P in water bodies is from fertilizer or from native soil P, farm management strategies should strive to (a) improve efficiency of delivering P to the crop by restricting the quantity of P applied to match the needs of the crop; (b) implement methods that intercept runoff or drainage P before it reaches water bodies; and (c) utilize practices that conserve soil and water. This study involved assessments of P losses from two agricultural watersheds in the Mississippi Delta with different management strategies. The Mississippi Delta region of the US is characterized by a relatively flat landscape, but significant water runoff and soil erosion losses have been documented (Locke, 2004). In water bodies of the Mississippi Delta region, long known for their fish productivity and recreational value, relatively few studies have evaluated P losses directly from Mississippi Delta soils. This paper reports on research that was part of a multi-agency project to assess the effects of agriculture in Mississippi Delta oxbow lake watersheds (Locke, 2004). Knight and Welch (2004) previously reported on levels of P in these lakes, and Rebich (2004) provided an initial report on agricultural runoff. This paper provides a more complete analysis of the agricultural surface runoff reported by Rebich (2004). The objectives of this paper are to improve the understanding of P losses and assess whether management practices might mitigate these losses. More specifically, we were trying to: 1) identify factors including fertilizer application timing and amount and the soil P level affecting P concentrations and losses after rainfall; and 2) explore potential relationships between P losses and runoff/sediment.

2. Materials and methods

2.1. Study area description and data collection

The Mississippi Delta Management System Evaluation Area (MSEA) project began in 1995 to study the impact of agriculture on water quality and to seek alternative innovative farming systems for improving water quality and ecology in the Mississippi Delta (Locke, 2004). The MSEA project involved several organizations and was led by the U.S. Department of Agriculture – Agricultural Research Service (USDA-ARS), U.S. Department of Geological Survey (USGS), and Mississippi State University. As part of the MSEA project, the USGS began stream flow and water quality monitoring in 1996 to help in assessing the effects of best management practices (BMPs) on water quality (Rebich, 2004). Data from three MSEA surface runoff monitoring sites (UL1, UL2 and BL3) were analyzed in this study (Rebich, 2004). UL1 and UL2 are subwatersheds of Deep Hollow Lake Watershed, located in Leflore County, Mississippi; and BL3 is a subwatershed of Beasley Lake Watershed, located in Sunflower County, Mississippi (Fig. 1). In 2004, Beasley Lake Watershed was also selected as one of 14 USDA-ARS Conservation Effect Assessment Project (CEAP) –Watershed Assessment Studies benchmark watersheds to assess environmental benefits derived from implementing USDA conservation programs (Locke et al., 2008).

During the study period from 1996 to 2000, conventional tillage practices in BL3 were used, while UL1 and UL2 were both managed as reduced tillage from 1996 to 1999, with a wheat cover crop planted by aerial seeding in the fall. Typically, conventional tillage in the Mississippi Delta region involves disking (to a depth of approximately 15 cm) in the fall after harvest, subsoil tilling once in the fall as needed, then disking and preparing plant beds in the fall, reforming beds in the spring, with cultivation during the growing season as needed. Reduced tillage usually involves disking (to a depth of approximately 15 cm) in the fall after harvest, fall subsoil tilling as needed, and then reforming the plant beds in the spring. Thus, all three sites received some tillage in the fall and spring. Cotton was planted in all study areas, except in 1998 when corn was planted in BL3 subwatershed. Site characteristics are summarized in Table 1, and agricultural management practices are summarized in Table 2.

Another management factor that was investigated was the use of modifications to drainage culverts positioned at low elevations in

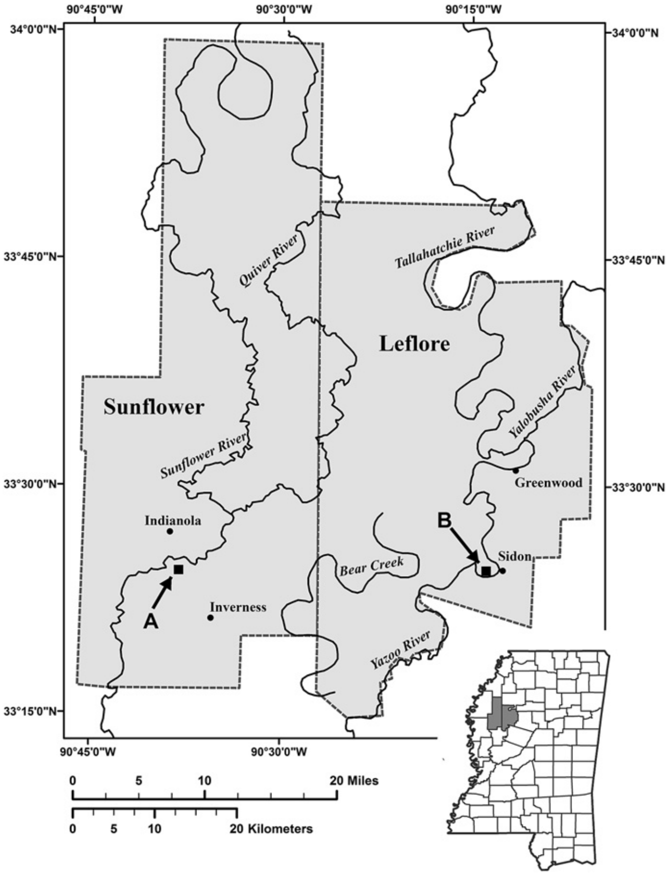

Fig. 1. Location of study watersheds: A). Beasley lake watershed where BL3 is located; and B) Deep Hollow Lake Watershed where UL1 and UL2 are located.

Table 1
Characteristics of monitoring sites.

Monitoring site	Drainage area (ha)	Mean Mehlich III P (ppm)[a]	Mean water-soluble P (ppm)[a]	Major soil type
UL1	17.0	37.8	0.7	Tensas silty clay loam (57%), Dubbs very fine sandy loam (37%), and Alligator clay (6%)
UL2	11.2	66.5	1.4	Tensas silty clay loam (50%), Dundee silt loam (18%), Alligator clay (18%), and Dubbs very fine sandy loam (13%)
BL3	7.2	35.7	1.2	Dundee silt clay loam (64%) and Forestdale silty clay (36%)

[a] Soil was sampled in spring, 1996.

a subwatershed (Locke, 2004). In BL3 and UL1 the drainage pipes were modified with slotted board risers at the culvert inlet directly upstream from the sampling point (Rebich, 2004). During fallow periods (generally October through March) or anticipated periods of heavy runoff, wooden boards were placed in the slots to impede water from entering the pipe. The boards were removed as water subsided allowing sediment to settle.

During the study period from 1996 to 2000, P fertilizer was applied once to UL1 and UL2 (in 1998) and twice to BL3 (in 1998 and 1999) (Table 2). Phosphorus was applied as triple superphosphate (0–30–0) to both UL1 and UL2 on October 6, 1998 at a rate of 9.5 kg P ha^{-1}. The P fertilizer was applied with a fertilizer spreader and was subsequently incorporated into the soil to a depth of 15 cm. For BL3, phosphorus was applied (knifed in) on April 20, 1998 at a rate of 6.4 kg P ha^{-1} (Table 2). Another P fertilizer application (knifed in as a side-dress) was made to BL3 on May 20, 1999 as 13–13–13 N–P–K at a rate of 19 kg P ha^{-1} (Table 2). No P fertilizer was applied in 2000 at any site.

The USGS installed three gauging stations in 1995–1996 to monitor runoff, sediment and nutrient loadings from all three study sites with one gauge for each site (Rebich, 2004). Continuous stream flow was monitored from 1996 to 2000 using critical flow flumes at UL1 and UL2 and using a weir equation at BL3. Stage was recorded using an Isco Model 4130 Flow Logger bubbler system at all three sites; Isco, Inc., Lincoln, NE). As stage increased at each site during a runoff event, automatic samplers were activated and retrieved up to 24 discrete samples during each event (Isco Model 3700 Portable Sampler). Discrete samplers were pulled based on flow-pacing schemes, not time-pacing. To explain flow-pacing, we developed "typical" flow hydrographs at each site during the installation year (1995). These varied from site to site and seasonally at each site. Stage-discharge relationships were programmed into the flow loggers at each site, then samples were pulled when a certain volume passed the sampling point during runoff events. This allowed more samples to be taken on the rising part of the hydrograph and peak of a runoff event, which is the time during each event that most of the sediment and nutrients were in the runoff, than on the falling part of the hydrograph. Water samples were transported to the USGS laboratories and analyzed for suspended sediment, TP (total P), and ortho-P (orthophosphate, PO_4–P) (Murphy and Riley, 1962). Colorimetry methods were used for ortho-P analysis (Fishman et al., 1994), and micro-Kjeldahl digestion methods were used for TP analysis (Patton and Truitt, 1992). All measurements followed USGS quality assurance/quality control (QA/QC) procedures. Precipitation was measured at all monitoring sites using a tipping bucket rain gauge. More details concerning sampling methods and analytical protocols were as described by Rebich (2004).

Table 2
Agricultural management practices for study sites.

Water year	Site	Crop and planting date	Tillage practice	P fertilizer application (kg P ha^{-1})	Date of fertilizer application (m/d/yr)
1997	UL1	Cotton 5/14/1997	Reduced tillage	–	–
	UL2	Cotton 5/17/1997	Reduced tillage	–	–
	BL3	Cotton 4/11/1997	Conventional tillage	–	–
1998	UL1	Cotton 5/5/1998	Reduced tillage	–	–
	UL2	Cotton 5/5/1998	Reduced tillage	–	–
	BL3	Corn 4/1/1998	Reduced tillage	6.4	4/20/1998
1999	UL1	Cotton 5/11/1999	Reduced tillage	9.5	10/6/1998
	UL2	Cotton 5/11/1999	Reduced tillage	9.5	10/6/1998
	BL3	Cotton 4/29/1999	Reduced tillage	19	5/20/1999
2000	UL1	Cotton 5/4/2000	Conventional tillage	–	–
	UL2	Cotton 5/4/2000	Conventional tillage	–	–
	BL3	Cotton 4/26/2000	Conventional tillage	–	–

2.2. Summary of monitoring data

The total sediment and P losses were calculated using discrete concentration data flow records at each site. Mass loads were then normalized by dividing each individual storm load by the drainage area and expressed as mass per area (g/ha.). A year of record was defined as beginning on October 1 from the previous year to September 30 of a current year, also referred to as a water year (WY) by the USGS. Thus, losses for WY 1997 were summed from October of 1996 through September of 1997. Sediment and P losses for each WY were summed to generate total WY losses. Total runoff from each monitoring site was also calculated and presented in mm for each WY.

To investigate the potential relationship between runoff and ortho-P losses, collected runoff and associated ortho-P from each rainfall event were plotted in an X, Y coordinate plane and regression analyses were performed. Similarly, to investigate the potential relationship between sediment and TP losses, collected sediment and associated TP from each rainfall event were also plotted in an X, Y coordinate plane and regression analyses were performed.

3. Results and discussion

3.1. Phosphorus concentrations in surface runoff

The average, range of concentrations, as well as concentrations in the runoff from the first three rainfall events after the application of P are presented in Tables 3 and 4. The rainfall amounts associated with the maximum concentrations and the first three rainfall events are also presented in Tables 3 and 4. The purpose of Tables 3 and 4 is to help identify relationships between P application, rainfall and P concentrations in the runoff water.

3.1.1. Ortho-P concentrations

No P fertilizer was applied in UL1 and UL2 in 1997, but the highest ortho-P concentration (0.96 mg P L^{-1}) was measured in runoff during entire study period (1997–2000) from UL1 during the fall season following harvest in 1997 (38.1 mm rainfall in Table 3). Very little runoff was collected at UL1 from that event, and no runoff was collected at nearby UL2. The low runoff volume

Table 3
Ortho-P and TP concentrations for selected runoff events at UL1 and UL2. From WY 1997 to WY 2000, there were 155 and 118 runoff events for UL1 and UL2, respectively.

Date	UL1			UL2		
	Rainfall (mm)	Ortho-P (mg L^{-1})	TP (mg L^{-1})	Rainfall (mm)	Ortho-P (mg L^{-1})	TP (mg L^{-1})
10/23/1997	38.1	0.96[a]	1.3	–	–	–
6/5/1998	25.9	0.11	1.7	21.3	0.21	6.0[a]
11/14/1998[b]	76.7	0.36	0.72	75.2	1.0[a]	1.4
11/20/1998[b]	25.7	0.25	0.86	24.6	0.66	1.1
12/07/1998[b]	42.7	0.16	0.46	36.3	0.65	0.8
6/17/2000	35.1	0.28	2.9[a]	35.1	0.47	1.7
Average		0.17	0.96		0.36	1.1
Range		0.01–0.96	0.16–2.9		0.06–1.0	0.14–6.0

[a] The highest concentrations observed during the monitoring period.
[b] First, second, and third rainfall events after P application. UL1 and UL2 received P fertilizer on October 6, 1998.

at UL1 may have minimized dilution, resulting in the relatively high concentration of ortho-P in runoff. The highest ortho-P concentration in runoff at UL2 (1.0 mg P L^{-1}) was observed on November 14, 1998 (75.2 mm rainfall), which was the first rainfall event after P fertilizer application. However, the ortho-P concentration in runoff was only 0.36 mg/L at UL1 during the same event with similar rainfall (Table 3). For the second and third precipitation events after P fertilizer was applied, ortho-P concentrations of 0.25 and 0.16 mg/L were measured in runoff at UL1; and 0.66 and 0.65 mg/L were observed at UL2 (Table 3). All ortho-P concentrations in runoff from those three 1998 rainfall events at UL1 and UL2 were higher than concentrations measured before P fertilizer was applied. It appears that fall P application after harvest tended to increase ortho-P concentrations in surface runoff, similar to other studies (Algoazany et al., 2007; Little et al., 2007). The higher ortho-P concentrations at UL2 than those at UL1 also may be due to higher soil P at UL2 (Table 1). A number of other studies have reported positive linear relationships between ortho-P concentrations in runoff and soil P levels (e.g., Daverede et al., 2003; Little et al., 2007; Pote et al., 1996, 1999; Sharpley, 1995).

At both UL1 and UL2, ortho-P concentrations measured in runoff during the spring–summer growing season were lower than those measured during the fallow fall–winter season. Hydrographs of selected runoff events at the UL2 site illustrate the seasonal differences observed in ortho-P runoff concentrations (Figs. 2 and 3). Ortho-P concentrations in UL2 runoff were relatively low during the 1998 growing season (Fig. 3A). Fertilizer P was applied in fall 1998, so it might be expected that the ortho-P concentrations at UL2 in the first runoff event after fertilizer application (Fig. 2A) would be higher than those previous to fertilizer application (0.21 vs. 1.0 mg P L^{-1}, Table 3). The ortho-P concentrations were less than 0.2 mg/L nine months after P application (July, 1999, Fig. 3B), but although no P fertilizer was applied in 1998, ortho-P concentrations at UL2 were again higher during the 1999 fallow fall-winter season (14 months after P was applied) (Fig. 2B). Similar patterns were observed at UL1. The lower ortho-P concentrations observed during the growing season at UL2 (Fig. 3) may have been due to plant uptake.

At the BL3 site, the highest ortho-P concentration of 0.7 mg/L was observed on August 11, 1997 with a rainfall of 36.1 mm (Table 4) although no P fertilizer was applied in the spring of 1997. Phosphorus fertilizer was applied in the spring of 1998 and 1999 (Table 2), but ortho-P concentrations in surface runoff during the first three rainfall events after P application were relatively low (Table 4). This may have been a combination of lessened availability of labile soil P due to plant uptake or fertilizer P retention in soil. Also, the application of P in a sub-surface band may have contributed to lower ortho-P losses in runoff. In contrast to UL1 and UL2, the ortho-P concentrations were also low from BL3 during fall and winter, possibly because P was applied in spring (Figs. not shown).

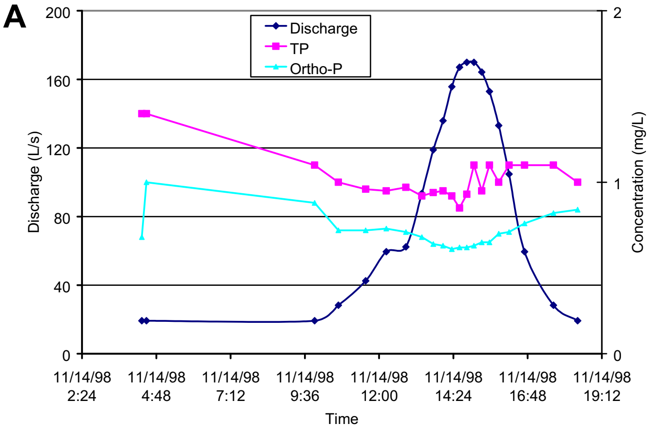

Fig. 2. Representations of concentrations of constituents in two selected runoff events during the fallow season at Deep Hollow Lake watershed, UL2 site: (A) discharge, TP and ortho-P concentrations observed on November 14, 1998, which was the first rainfall event after P was applied at UL2 (approximately one month after application); and (B) discharge, TP and ortho-P concentrations observed on December 12, 1999, approximately one year after P was applied at UL2.

3.1.2. *TP concentrations*

TP concentrations of 0.72 mg/L at UL1 and 1.4 mg/L at UL2 were observed during the first rainfall after the application of fertilizer P (Nov. 14, 1998) (Table 3). However, the highest TP concentrations in runoff at UL1 and UL2 (2.9 mg/L on 6/5/1998 and 6.0 mg/L on 6/17/2000, respectively) were not associated with fertilizer applications (Table 3) nor did they coincide with high ortho-P concentrations in runoff. For BL3, the highest TP concentration of 7.9 mg/L was observed on May 5, 1999, with a rainfall of 30.2 mm (Table 4) before the second P application. It appears that the highest TP concentrations occurred in late spring or summer at all three sites. Other studies have reported the greatest TP losses in runoff in the spring (Daverede et al., 2003; Little et al., 2007).

In summary, among the three study sites, the highest ortho-P concentrations tended to occur in fall or winter, while the highest TP concentrations occurred in spring or summer (Tables 3 and 4). UL2 had the highest soil P level (Table 1), and this may have contributed to increased ortho-P concentrations in runoff. Although BL3 had the lowest mean ortho-P concentration, it had the highest mean TP concentration, perhaps associated with a combination of

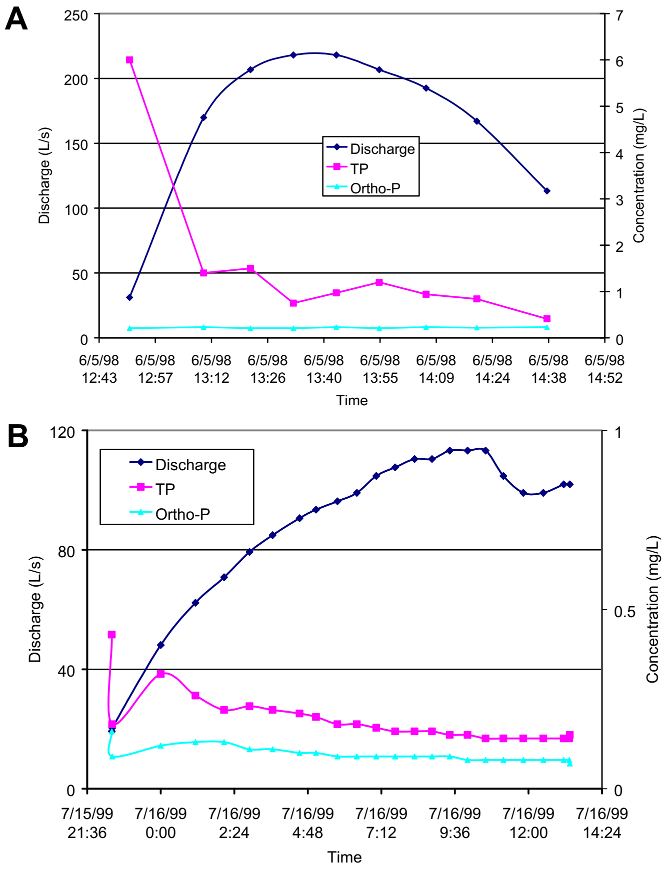

Fig. 3. Representations of concentrations of constituents in two selected runoff events during the growing season at Deep Hollow Lake watershed, UL2 site: (A) discharge, TP and ortho-P concentrations observed on June 5, 1998 which was the growing season before P was applied at UL2; and (B) discharge, TP and ortho-P concentrations observed on July 16, 1999, the first growing season after P was applied (approximately 9 months after application).

increased sediment loss due to tillage, recent P fertilizer application and high percentage of clay content (Table 1). However, enhanced plant uptake during the growing season may have contributed to reduced ortho-P losses in surface runoff. In addition, UL2 had higher mean ortho-P and TP concentrations than UL1 (Table 3). A higher soil P level at UL2 than UL1 (Table 1) may explain this phenomenon. Other studies also reported that higher P concentrations in runoff are related to the higher soil P levels (Bertol et al., 2007; Little et al., 2007; Sharpley, 1995). Finally, higher ortho-P and TP concentrations did not always correspond with immediate P fertilizer application; and higher rainfall did not always cause higher P concentrations, indicating that more detailed study is needed to determine which other factors are contributing to P loss in runoff.

Table 4
Ortho-P and TP concentrations for selected runoff events at BL3. From WY 1997 to WY 2000, there were 108 runoff events for BL3.

Date	Rainfall (mm)	Ortho-P (mg L^{-1})	TP (mg L^{-1})
8/11/1997	36.1	0.7[a]	1.9
4/28/1998[b]	29.5	0.11	0.87
5/29/1998[b]	85.5	0.22	3.8
6/05/1998[b]	20.8	0.09	0.6
05/05/1999	30.2	0.15	7.9[a]
5/31/1999[c]	34.8	0.25	1.5
6/02/1999[c]	10.4	0.16	3.0
6/13/1999[c]	27.7	0.27	5.6
Average		0.12	1.29
Range		0.02–0.7	0.17–7.9

[a] The highest concentrations observed during the monitoring period.
[b] First, second, and third rainfall events after P application in 1998. BL3 received P fertilizer on April 20, 1998.
[c] First, second, and third rainfall events after P application in 1999. BL3 received P fertilizer on May 20, 1999.

3.2. Annual P losses from three study sites

Annual losses of ortho-P and TP were analyzed to determine whether annual P losses corresponded with factors such as P fertilizer application, modification of drainage culverts with slotted board risers, planting and tillage, soil P level/soil texture, or precipitation. Annual rainfall, total runoff, ortho-P loss, sediment loss and TP loss are presented in Figs. 4 and 5 to show annual P losses among study years at individual study sites.

The greatest annual rainfall for both UL1 and UL2 occurred in WY 1997 and WY 1998 (Fig. 4). Although less runoff was observed for the UL1 site in WY 1999 than in WY 1998 (Fig. 4), the highest ortho-P loss for UL1 during the four-year study period occurred in WY 1999 (Fig. 4), and this might be partially attributed to the 1998 fall P application. Similarly, the highest ortho-P loss during the four-year study for UL2 was in WY 1999 (Fig. 4), although runoff values for WY 1997 and WY 1999 were similar (Fig. 4). In the Mississippi Delta region, high intensity rainfall and higher total rainfall usually occur during the winter months (Yuan et al., 2001). Since more runoff is usually observed in the winter due to the rainfall patterns, fall P fertilizer application in 1998 (Table 2) may account for the higher ortho-P losses at UL1 and UL2 for WY 1999 than was observed in other years. Similar to ortho-P, the highest TP loss at UL2 (Fig. 5) was also during WY 1999, but comparably high TP losses were not observed in UL1. Therefore, although the P fertilizer application in fall 1998 may have contributed to some of the increased loss of TP in UL2, it was apparently not the only factor. A combination of higher clay content/higher P in UL2 soils and the use of slotted board risers in UL1 drainage culverts may help to explain the lower TP runoff in UL1. However, no apparent effect of the slotted board risers in the drainage culvert in UL 1 was observed in other years.

At BL3, TP loss was high in WY 1998 and WY 1999, likely due to P fertilizer application and tillage in the spring of each year. The greatest TP loss at BL3 occurred in WY 1998 (Fig. 5), and was

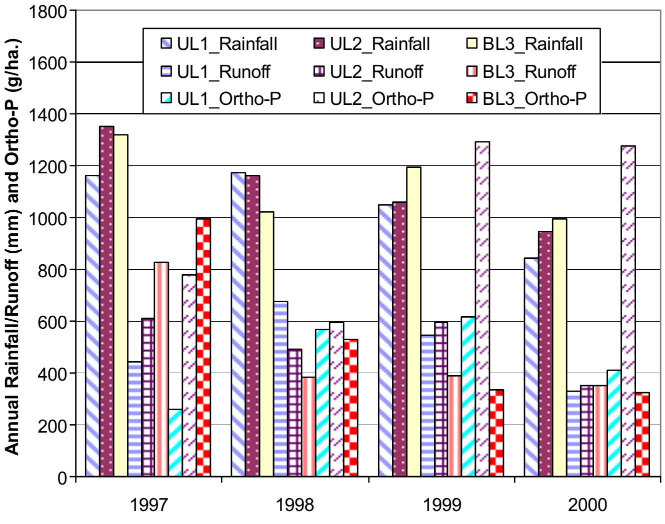

Fig. 4. Total water year rainfall, runoff and ortho-P losses at study sites.

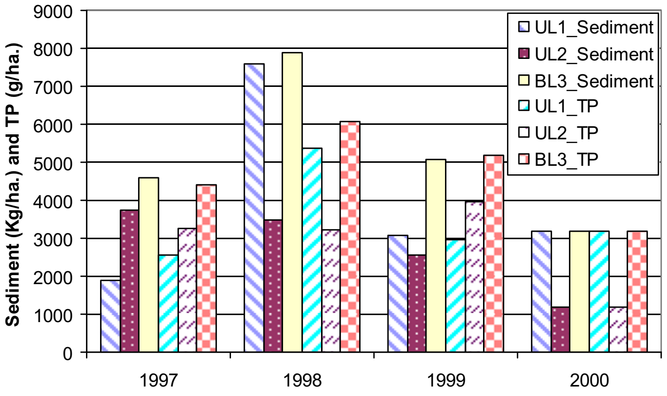

Fig. 5. Total water year sediment and TP losses at study sites.

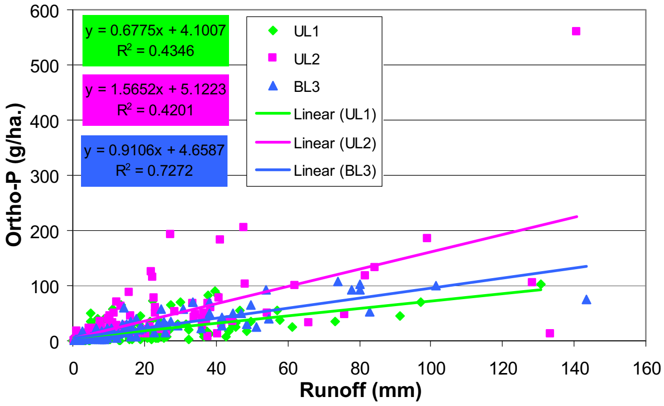

Fig. 6. Relationship between runoff and ortho-P at study sites.

probably associated with high sediment loss that year (Fig. 5). Although the sediment loss in WY 1998 was much more than in WY 1999 (Fig. 5), TP loss in WY 1998 was not much higher than in WY 1999 (Fig. 5), perhaps because almost three times more fertilizer P was applied in 1999 than in 1998 (Table 2). Since P fertilizer was applied at BL3 in the spring before planting, the tillage associated with planting might have caused sediment loss that resulted in higher TP loss. Although TP runoff losses at BL3 were generally associated with P fertilizer application, tillage, and sediment runoff, ortho-P runoff patterns were less clear. The highest annual ortho-P loss at BL3 was observed in WY 1997 (Fig. 4), corresponding to the highest annual rainfall and runoff (Fig. 4). However, no P fertilizer was applied that year, although P fertilizer was applied in 1998 and 1999 when ortho-P runoff losses were less than half that of WY 1997. The lower ortho-P losses in WY 1998 and WY 1999 are primarily attributed to lower runoff losses relative to rainfall (runoff: rainfall in WY 1997 was 0.62 vs. 0.39 and 0.33 in WY 1998 and WY1999, respectively).

3.3. *Relationships among runoff: ortho-P loss, sediment: TP loss, management, and site-specific properties*

Previous studies on the fate of P have demonstrated the complexity of relationships among management practices and assessment of agriculturally applied P (e.g., Daverede et al., 2003; Little et al., 2007; Udawatta et al., 2004). Similarly, in the current study, patterns for P losses, P application and other management practices, rainfall, runoff and sediment varied from one site to another, and relationships among these factors were not always straightforward. Comparisons among the three subwatersheds reported in this paper can be made that may lead to some conclusions relative to management parameters, site-specific soil properties, and runoff parameters.

Correlations of ortho-P with runoff events were examined for each subwatershed (Fig. 6). Ortho-P losses tended to increase with surface runoff for all three study sites (Fig. 6) similar to results observed in other studies (Algoazany et al., 2007; Gentry et al., 2007; Little et al., 2007). The higher regression slope for UL2 indicates a higher proportion of ortho-P loss for the same volume of runoff. As shown earlier, ortho-P concentrations (Tables 3 and 4) and losses (Fig. 4) from UL2 were the highest among the three sites during the monitoring period. In three of the four years studied, ortho-P losses from UL2 were the highest among the three sites (Fig. 4) even though UL2 received the same amount of P fertilizer as UL1 and less P fertilizer than the BL3 (Table 2). The ortho-P loss at UL2 was more than twice that of UL1 and BL3 in WY 1999 and WY 2000 (Fig. 4), but the runoff observed at UL2 was either equal to or slightly greater than at either of the other two sites (Fig. 4). For the two subwatersheds with the same soil series (UL1 and UL2), the ratio of ortho-P to TP in runoff was greater for UL2 than for UL1 every year (i.e., in UL2, a greater proportion of TP was comprised of the soluble fraction, ortho-P). These observations indicate that the primary factor contributing to higher ortho-P loss in UL2 was higher soil P than at the other two sites (Yuan et al., 2009; Locke et al., 2001). One out of four years studied (WY 1997), BL3 had the highest ortho-P loss. No fertilizer was applied during that time, but the higher ortho-P loss in WY 1997 may be partially attributed to the use of conventional tillage management that may have contributed to increased runoff (Fig. 4).

Correlations of TP with sediment for individual rainfall events were also examined for each subwatershed (Fig. 7). The loss of TP was strongly correlated with sediment loss for all three subwatersheds as shown in Fig. 7 (Linear regressions of sediment and TP resulted in an R-square of 0.66 at UL1, an R-square of 0.76 at UL2; and an R-square of 0.70 at BL3). Similar to the relationship of ortho-P with runoff, the higher regression slope of TP and sediment for UL2, indicating higher TP loss for the same quantity of sediment loss, was attributed to a higher level of P in soil. Although the highest ortho-P occurred at UL2, BL3 had the highest TP in three of four study years (Figs. 4 and 5). The soils at BL3 were managed under conventional tillage two of the four years, and every year, BL3 sustained the highest sediment loss. The higher TP loss at BL3 was therefore likely associated with the sediment loss resulting from more intensive tillage (Fig. 5).

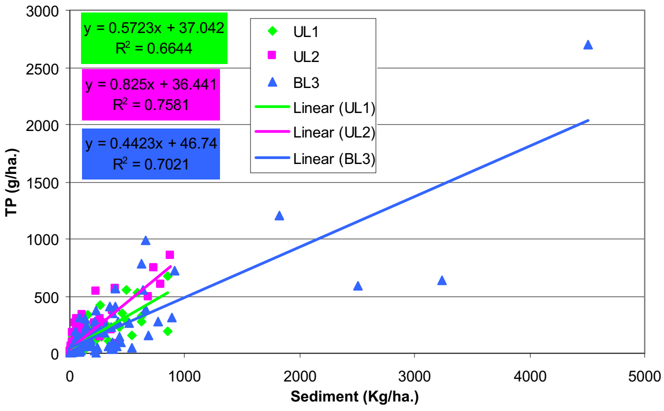

Fig. 7. Relationship between sediment and TP at study sites.

4. Summary and conclusions

This study of three Mississippi Delta subwatersheds demonstrated the complexity of assessing the fate and transport of P in agricultural watersheds. Consistent with other studies, high P concentrations in surface runoff resulted from factors such as P application, rainfall, soil P levels and soil tillage. For all three watersheds, ortho-P loss was related to surface runoff volume while TP loss was more closely related to sediment loss. For example, a combination of recent applications of P in the fall and high rainfall in the fall and winter resulted in greater ortho-P losses, indicating that P application early in fallow periods should be discouraged. However, P application in spring and spring tillage resulted in more TP loss due to higher levels of sediment loss caused by tillage prior to planting.

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