Landscape and Watershed Processes

Phosphorus Loss and Runoff Characteristics in Three Adjacent Agricultural Watersheds with Claypan Soils

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ABSTRACT

Effects of precipitation, runoff, and management on total phosphorus (TP) loss from three adjacent, row-cropped watersheds in the claypan region of northeastern Missouri were examined from 1991 to 1997 to understand factors affecting P loss in watersheds dominated by claypan soils. Runoff samples from each individual runoff event were analyzed for TP and sediment concentration. The annual TP loss ranged from 0.29 to 3.59 kg ha^{-1} with a mean of 1.36 kg ha^{-1} across all the watersheds during the study period. Significantly higher loss of TP from the watersheds was observed during the fallow period. Multiple small runoff events or several large runoff events contributed to loss of TP from the watersheds. Total P loss in 1993, a year with above-normal precipitation, accounted for 30% of the total TP loss observed over seven years. The five largest runoff events out of a total of 66 events observed over seven years accounted for 27% of the TP loss. The five largest sediment losses were responsible for 24% of the TP loss over seven years. Runoff volume and sediment loss explained 64 to 73% and 47 to 58% of the variation in TP loss on watersheds during the study. Flow duration and maximum flow accounted for 49 and 66% of TP loss, respectively. The results of this study suggest that management practices that reduce runoff volume, flow duration, maximum flow, and sediment loss, and that maintain a suitable vegetative cover throughout the year could lower P loss in claypan soils.

The impact of agricultural activities on P water pollution continues to be a serious public concern. During the last 20 yr, the effects of nonpoint-source pollution have received increasing global attention (Abu-Zreig et al., 2003). A connection between agriculturally derived P movement to surface waters and eutrophication has been well-established (Cassell et al., 1998; Correll, 1998; Sharpley et al., 1994; Zaimes and Schultz, 2002). The control of P entering water resources is of prime importance in reducing accelerated eutrophication in fresh waters since P is often the growth-limiting element in most freshwater environments (Daniel et al., 1998; Klatt et al., 2003). Therefore, regulatory authorities, land owners, and state agencies need relevant information on factors affecting P in runoff on a watershed scale to select appropriate regulations to protect water bodies. States are required to adopt water quality standards by 2004 using the criteria published by the USEPA or other scientifically defensible methods (Ice and Binkley, 2003). However, insufficient data are available relating P loss and landscape features, precipitation, management, and runoff characteristics on a watershed scale for the development and effective implementation of P control practices. Such information is especially limited in regions dominated by soils with relatively shallow restrictive subsoil horizons, such as claypan soils, which may increase the magnitude of P loss and runoff.

The main mechanism by which P is lost from row-cropped agricultural land is by runoff carrying both soluble and particulate forms of P (Quinton et al., 2001; Sharpley et al., 1994). For example, Catt et al. (1998) showed that losses of P from experimental plots in the UK occur mainly in particulate forms and are consequently greater in surface runoff than drain flow. Particulate P is usually the largest fraction of P in runoff from row-crop production systems due to greater losses of sediment in this type of production system (Sharpley et al., 1992).

Finer soil particles can carry a higher concentration of sorbed nutrients than the bulk soil (Sharpley and Smith, 1991). Comparing P loss and suspended sediment loss, Wall et al. (1996) showed that the ratio of TP to sediment loss increases with decreasing sediment loss because low erosion or sediment transporting runoff events carry smaller clay-size sediment particles, which have more readily sorbed P. This, in turn, results in a larger mass of P per unit of total solids from small runoff events. However, the relationship between sediment loss and P loss appears to vary greatly from one area to another because geochemical properties of runoff sediment vary according to the source (Williams et al., 1980; Grobler and Silberbauer, 1985). In southern Idaho, Westermann et al. (2001) showed that TP in runoff was not statistically related to soil test P but was linearly related with sediment concentration. In the Coastal Plain of Maryland, P and sediment concentrations in runoff were correlated, but the correlation relationships differed among the 17 watersheds that were studied (Jordan et al., 1997).

Claypan soils in central and northeast Missouri have an argillic horizon with a content of 40 to 50% smectitic clays between 10 and 80 cm below the surface. These soils are characterized by very low infiltration rates (Jamison and Peters, 1967). Due to this low permeability, claypan soils perch water and create lateral flow above the claypan (Blanco-Canqui et al., 2002). In northern Missouri,

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Abbreviations: TP, total phosphorus.

the relative proportions of surface and subsurface flow in a claypan soil on row-cropped watersheds varied between management, with greater subsurface flow on a claypan soil watershed with a riparian buffer compared with a watershed with grass filter strips (Schmitt, 1999). This observation is further supported by a study in forested watersheds where increased tree cover and subsequent rooting enhanced water infiltration (DeWalle et al., 1988). Claypan soils in the study area are classified in hydrological group D and are capable of producing runoff volumes of over 75% of the precipitation, depending on antecedent soil moisture (Schwab et al., 1993; Watson, 1979). Since claypan soils generate high flow rates during runoff events, significant losses of soil P may leave agricultural watersheds in runoff. Spatial variation in depth to claypan across agricultural fields also has been observed to influence crop yields (Kitchen et al., 1999) and water and chemical movement (Blevins et al., 1996; Blanco-Canqui et al., 2002). However, little research is available examining soil P loss in claypan soils on a watershed scale.

Factors affecting the loss of P in runoff include runoff volume, sediment loss, forms and concentration of soil P, and depth of mixing of the soil and water (Cassell et al., 1998; Sharpley et al., 1994). Other parameters, such as precipitation and soil surface characteristics that vary temporally and spatially, are also important in determining P loss on a watershed scale (Gburek et al., 2002). Phosphorus exports from watersheds also vary widely over individual storm events, annual cycles, and long periods of time (Cassell et al., 1998; Quinton et al., 2001). In a 28-yr study, Edwards and Owens (1991) showed that the largest three erosional events caused more than 50% of the soil loss measured in Coshocton, Ohio. This observation has also been supported by research in the UK (Morgan et al., 1986) and Nigeria (Lal, 1976). Small rainfall events that occur more frequently and require less energy to detach soil particles can also cause significant soil losses. Quinton et al. (2001) showed that smaller events accounted for a greater proportion of P loss over a 6-yr study than infrequent larger events.

The concentration of P in runoff is largely determined by timing of precipitation and vegetative cover because precipitation provides the major source of energy for transport. In a simulated rain study, Edwards et al. (2000) showed that the magnitude of P loss was related to the proximity of preceding rainfall. Therefore, antecedent soil moisture affects P transport (McDowell and Sharpley, 2002).

Row-crop agriculture under conventional tillage as practiced in much of the U.S. Midwest increases P loss due to the presence of a bare soil surface during spring and late fall. The soil in this condition is susceptible to raindrop impact and often contains added P from fertilizer or animal waste. In northeastern Missouri, approximately 35, 28, 23, and 14% of the precipitation occurs in spring, summer, fall, and winter months, respectively. Approximately 34 to 36% of the precipitation occurs between October and March when the ground is rarely covered with crops (Owenby and Ezell, 1992).

We hypothesized that the presence of claypan soils, characterized by a high-clay subsoil that restricts drainage, would increase P losses in runoff. The objectives of this research were to (i) examine the effects of landscape and watershed characteristics on soil P loss over time by comparing three adjacent watersheds, (ii) determine the impact of small and large runoff events and runoff characteristics (duration and peak height) on TP loss, and (iii) evaluate the effects of the timing of rainfall on P loss in relation to the type and duration of vegetative cover.

MATERIALS AND METHODS

Watersheds and Management

The study was conducted at the University of Missouri's Greenley Memorial Research Center in Knox County, Missouri, USA (40°01′ N, 92°11′ W) from 1991 to 1997. Three adjacent north-facing small watersheds designated as "east," "center," and "west" with land areas of 1.65, 4.44, and 3.16 ha, respectively, were instrumented with flumes and flow measuring and sampling devices in 1991 (Fig. 1). Each watershed is drained by a grass waterway that leads into a concrete approach structure and an H-flume. The east watershed has a 0.91-m flume while the other two watersheds have 1.37-m flumes (Udawatta et al., 2002).

The parent materials for the soils in the watersheds are glacial till and wind-blown loess. Based on soil survey information, Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs), Kilwinning silt loam (fine, smectitic, mesic, Vertic Epiaqualfs), and Armstrong loam (fine, smectitic, mesic, Aquertic Hapludalfs) were the primary soils in the three watersheds (Watson, 1979). Kilwinning and Putnam soils are formed in silty and clayey material and are somewhat poorly drained and poorly drained, respectively. Armstrong soils are formed in glacial till

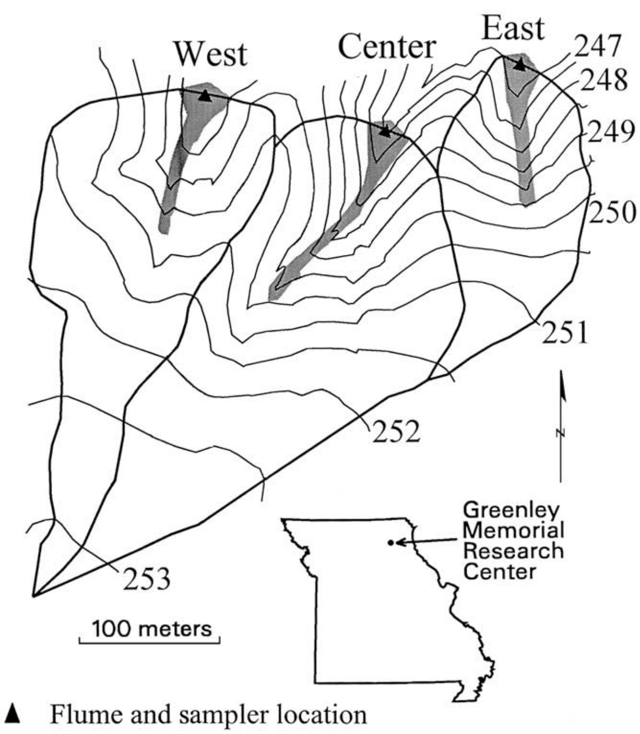

Fig. 1. Study site location in Missouri and 0.5-m interval contour lines on east, center, and west watersheds. Gray bands indicate location of the grass waterways.

and are moderately well drained (Watson, 1979). The Putnam soils occur on nearly level (0–1% slope) areas while the Kilwinning soils occur downslope from the Putnam on 2 to 5% slopes. Armstrong loam soils occur on 5 to 9% slopes.

Thirty-year mean annual precipitation in the region is 920 mm per year, of which more than 66% falls from April through September (Owenby and Ezell, 1992). Mean annual air temperature is approximately 11.7°C with an average monthly low of −6.6°C in February and an average monthly high of 31.4°C in July (Owenby and Ezell, 1992). Snowfall averages about 590 mm per year, and snow can stay on the ground for extended periods.

Agricultural activities in the watersheds including the crops grown, field preparation, fertilizer regime, and grain yields from 1991 to 1997 are summarized in Table 1. Before 1991, the field containing these watersheds was in a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation with planting occurring in a north–south direction perpendicular to the contour, except for some areas near the waterways. Beginning in 1991, planting was in a straight row perpendicular to the slope and then beginning in 1996 was on the contour. During the study period, the land preparation method was no-till with the exception of 1992 when watersheds were field-cultivated with a John Deere (Moline, IL) E1000 field cultivator.

Sample Collection and Analysis

One-meter-deep soil samples were collected from all three watersheds using a Giddings (Windsor, CO) probe with a 5-cm-diameter steel core to determine variability across the watersheds in depth to the top of the claypan layer. Thirty soil cores from the west watershed were collected in 1994. In year 2000, an additional 30 and 18 soil cores were collected from the center and east watersheds, respectively. Soil cores were separated by horizon and soil texture was determined by the pipet method (Soil Survey Staff, 1991). In 1994, composite soil samples from a depth of 20 cm were taken from each watershed and extracted for soil test P with Bray-1 extractant and analyzed colorimetrically using the ascorbic acid molybdenum-blue method (Frank et al., 1998).

Stevens Type F water level recorders (Stevens Water Resources, Beaverton, OR) were used to measure runoff from 1991 to 1995. During that period, water level recorders remained in the field throughout the year. Isco (Lincoln, NE) bubbler flow measuring devices and Isco 3700 samplers replaced float recorders in August 1995. Isco instruments were installed each year in late February or early March to record flow rate and sampling times and collect runoff samples. These samplers were removed from the field in late December to protect them from possible damage due to freezing. Therefore, the sample collection period during 1995 and 1996 extended from March to December. In 1997, the sample collection period was from March to the end of June. Flow measuring devices engage the sampler to withdraw a 135-mL sample of runoff after each 25 m^3 of flow occurs. Therefore, runoff samples were flow-weighted and collected for individual storms. During the 7-yr study, 67, 67, and 64 runoff events generated runoff samples on the east, center, and west watersheds, respectively. For some consecutive events (maximum 2), samples were not separated by event. An average of 43 runoff events across the three watersheds over the 7-yr period did not generate sufficient runoff to activate the sampler. The runoff collection device of the west watershed was damaged by lightening and, therefore, it missed three sampling events. Flow rate, water level, runoff duration, and sample intake time data were downloaded from the Isco flow meters to a laptop computer following runoff events.

Isco flow meter data were used to estimate runoff duration and maximum flow rates (Isco, 1998). Isco flow-level data show the beginning and end of a flow event with the corresponding time. The duration of a flow event was determined using these corresponding times. The runoff level data were used to record the maximum flow rate of a runoff event. Flow duration and respective maximum flow levels were difficult to determine from runoff charts that were used from 1991 to 1995 since charts were replaced once a week and the recording of more than one event often occurred during the week. Therefore, data presented for runoff duration and maximum flow are from 1995 to 1997.

Chemical and physical analyses of composite runoff water samples were performed in the Forest Hydrology Laboratory at the University of Missouri. A known volume (20–250 mL depending on the sediment concentration) of a well-mixed runoff sample was filtered through a preweighed Whatman (Maidstone, UK) 934-AH glass microfiber using a vacuum pump to estimate sediment concentration (American Public Health Association, 1992). These filters were dried at 105°C to a constant weight and their dry weights were recorded. The difference between two dry weights and the filtered sample volume was used to estimate the concentration of total suspended sediment.

Unprocessed samples were refrigerated at 4°C until analysis. From 1991 to 1994, acid digested unfiltered runoff samples were analyzed by the ascorbic acid–molybdate colorimetric procedure using a Technicon (Tarrytown, NY) Autoanalyzer (Technicon, 1978). After 1994, TP was determined using an ammonium peroxidisulfate digestion followed by an ascorbic acid–molybdate procedure on a Lachat (Milwaukee, WI) Quickchem Automated Ion Analyzer (Liao and Marten, 2000). The detection limit for the method was 0.9 $\mu g\ L^{-1}$. Several samples from 1991 to 1994 were reanalyzed using the

Table 1. Summary of agricultural activities on the east, center, and west watersheds from 1991 to 1997.

Year	Crop	Variety	Planting date	Field preparation	Planting method	Grain yield	Fertilizer N–P–K
						kg ha^{-1}	kg ha^{-1}
1991	corn	–†	20 May	no-till	straight row‡	–†	–†
1992	soybean	–†	8 June	field cultivate	straight row‡	1 680	none
1993	corn	Pioneer 3394	1 June	no-till	straight row‡	8 152	160–50–100
1994	soybean	Pioneer 9362	18 May	no-till	straight row‡	3 695	none
1995	soybean	Golden Harvest	21 June	no-till	straight row‡	2 849	0–40–120
		Dekalb				2 130	
		Houston 3				6 119	
1996	corn	Lewis 4503	25 April	no-till	on contour	10 660	59–0–0
			5 June				
1997	soybean	Pioneer 9363	16 May	no-till	on contour	2 822	none

† Information not available.
‡ Perpendicular to slope.

ammonium peroxidisulfate digestion and the Lachat Autoanalyzer to compare the two procedures. Results showed no significant differences in TP concentration between the two digestion and analytical procedures.

Statistical Analysis

Statistical analyses of the data were performed using Statistical Analysis Systems software (SAS Institute, 1999). Least square linear regression analysis (PROC REG) was used to describe relationships between runoff and TP loss, runoff duration and TP loss, and peak flow and TP loss. The nonlinear relationships between TP and sediment loss were determined with SAS (PROC NLIN). Differences between regression coefficients or slopes of any two regressions ($p < 0.05$) were determined by testing the homogeneity of regression coefficients.

RESULTS AND DISCUSSION

Precipitation and Total Phosphorus Loss

A comparison of precipitation distribution and planting dates during the study showed that most of the precipitation occurred during the fallow period (Fig. 2). In general, corn and soybean cropping seasons were approximately 5 to 6 and 4 to 5 mo, respectively. Soybean was planted in 1995 instead of corn due to excessively rainy conditions in May. Corn was replanted in 1996 due to excessively rainy conditions during the planting period.

The annual discharge of TP from the three watersheds differed among years. Among the three watersheds, the west watershed had the lowest (0.29 kg ha^{-1} in 1997) and the highest annual losses (3.59 kg ha^{-1} in 1993) during the study (Fig. 3). The mean annual TP loss for the three watersheds across all years was 1.36 kg TP ha^{-1}. Annual P discharges reviewed by Beaulac and Reckow (1982) in non-claypan soils averaged around 0.2 kg ha^{-1} for forests, 1 kg ha^{-1} for pasture, and 2 kg ha^{-1} for row crops. In Kansas on non-claypan soils, 3-yr average P losses were 1.83, 1.83, and 1.1 kg ha^{-1} on chisel-disk, ridge-till, and no-till treatments, respectively (Janssen et al., 1996). Their average annual P loss was 1.59 kg ha^{-1} across the three treatments. Based on literature and USGS estimates, Snyder et al. (1999) estimated that the average loss of P in the Mississippi River basin in non-claypan soils was below 1.1 kg ha^{-1} yr^{-1}. The 7-yr mean reported here is smaller than that reported by Beaulac and Reckow (1982) and higher than reported by Janssen et al. (1996) for no-till treatments. The difference in observed P losses of this study compared with other research could be due to differences in landscape features and soil conditions (Fig. 1, Table 2). The watersheds of this study were on a corn–soybean rotation and annual fertilizer P applications were limited to the corn phase of the rotation (Table 1). In addition, the watersheds were under no-till management. Previous research has shown that conservation tillage decreases runoff and sediment losses compared with conventional tillage (Baker and Johnson, 1979; Sauer and Daniels, 1986).

The three watersheds lost an average of 2.86 kg TP ha^{-1} yr^{-1} in 1993 over 20 runoff events when the area received 42% more precipitation than the long-term annual mean. The TP loss in 1993 accounted for 30% of the total 7-yr loss. The TP loss from east, center, and west watersheds was 1.74, 3.25, and 3.59 kg ha^{-1} in 1993, respectively, while the 7-yr average for the three watersheds was 1.36 kg ha^{-1}. As precipitation increased, TP loss increased from the three watersheds and the annual precipitation explained 68% of the variation in TP loss ($p = 0.09$) during the study.

During the 7-yr study, the east, center, and west watersheds lost a total of 8.35, 8.93, and 11.22 kg TP ha^{-1}, respectively. The annual TP discharges were larger for the west watershed than for the other two watersheds except for 1994 and 1997 when the east watershed had larger losses (Fig. 3). In 1994, average Bray-1 soil test P was lower on the west watershed (47 kg ha^{-1}) compared with the other two watersheds. The east watershed (54 kg ha^{-1}) had the highest average Bray-1 soil test P while the concentration was intermediate on the center watershed (52 kg ha^{-1}). Despite having lower soil test P, the west watershed lost more TP than the other two watersheds over the whole 7-yr study and during five individual years. In an irrigation study, Aase et al. (2001) also observed that total P in runoff and soil P were not related.

Despite the close proximity of the three watersheds in this study, several inherent physical differences existed among the three watersheds that may have affected observed P losses possibly due to their effects on surface and subsurface flow of water across the watersheds. The area of the center and west watersheds was larger than the east watershed (Table 2). In addition, the east, center, and west watersheds had total slope lengths measuring 234, 425, and 383 m and with corresponding 2.1, 1.3, and 0.9% slopes along the entire watershed (Fig. 1, Table 2). The lowest 100 m of east, center, and west watersheds had slope segments with 3, 2, and 1.75% slopes, respectively.

Depth to claypan (Bt horizon) varied by landscape position (Table 2) and this characteristic may also influence surface and subsurface flow because soils with a shallower depth to the claypan would tend to have higher rates of lateral flow (Blanco-Canqui et al., 2002). The depth to the claypan in the upper one-third of each watershed was deeper than the lower one-third. Soils in the lower one-third of each watershed were sampled from erosional side slopes and dissected areas compared with more leveled areas in the upper one-third of each watershed. The depth to the claypan was much greater at all landscape positions in the west watershed than the other two watersheds. Waterways had the deepest soils above the claypan in each watershed. The average depth to the claypan in the waterways was 49, 62, and 57 cm for the east, center, and west watersheds, respectively. Despite greater depth to the claypan in the cropped area and grass waterways on the west watershed, more P was lost from the west watershed.

The grass waterways located at the base of each watershed may have reduced TP loss on the three watersheds. Approximately 44, 35, and 27% of the total watershed length on the east, center, and west watersheds, respec-

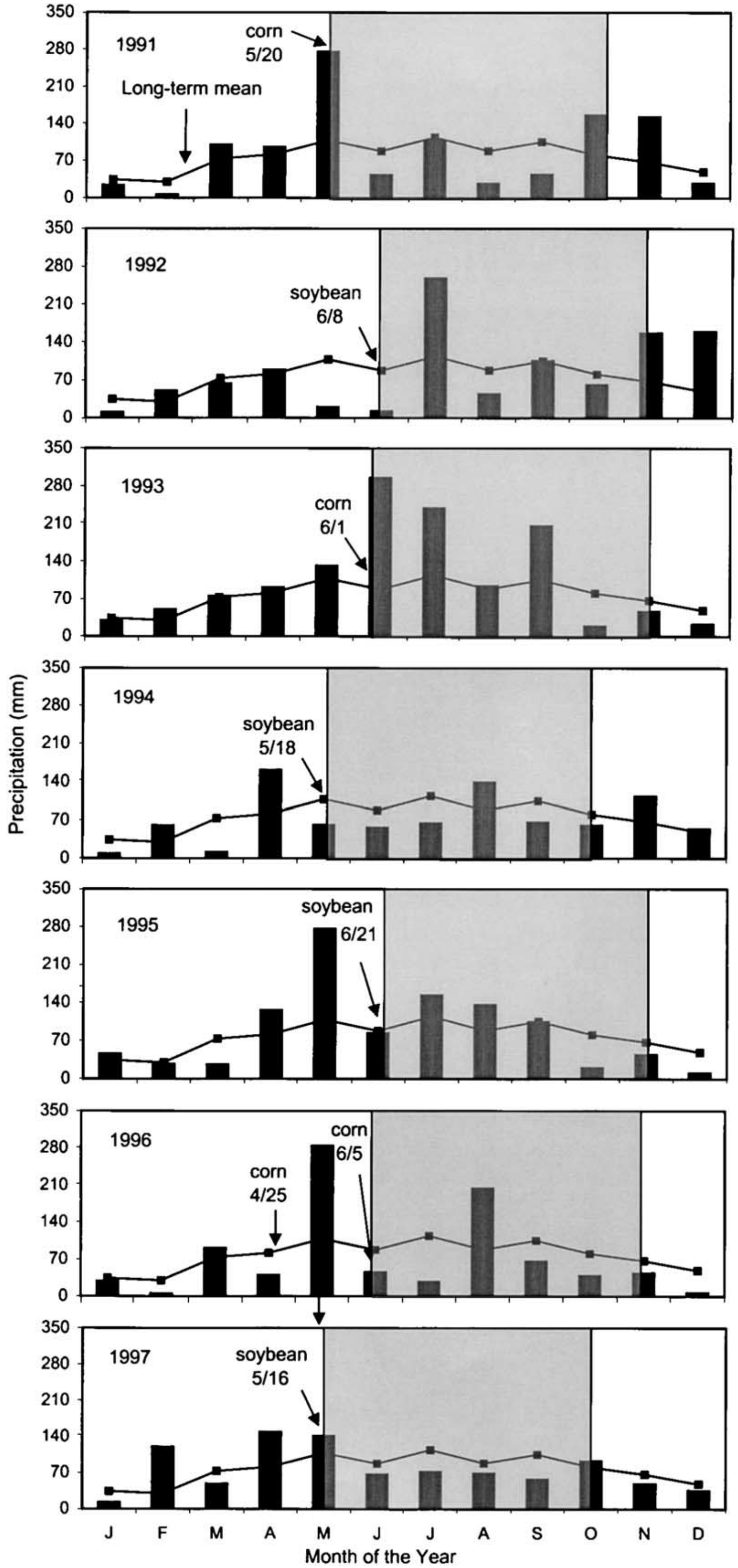

Fig. 2. Monthly precipitation distribution, crop type, and planting dates at the Greenley Center from 1991 to 1997. The line represents the long-term monthly mean precipitation from 1961 to 1990. The gray areas represent cropping periods.

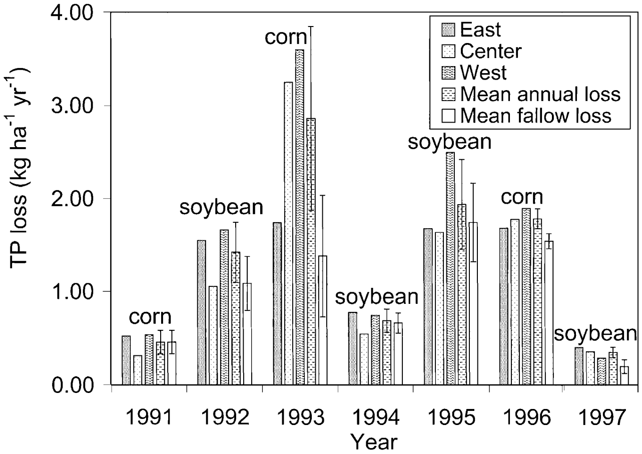

Fig. 3. Annual total phosphorus loss for the east, center, and west watersheds and the mean annual and fallow period total phosphorus losses across all watersheds from 1991 to 1997. Bars indicate ±1 standard deviation for the mean annual and fallow period total phosphorus losses across all watersheds.

tively, was occupied by grass waterways (Table 2). The lower proportion of the watershed length in grass waterway may have been one reason that the west watershed lost 1.34 and 1.25 times more TP than the east and center watersheds, respectively, during the 7-yr period. In findings reported by Dillaha et al. (1989), orchard grass filter strips of 9.1 and 4.6 m in width removed 79 and 61% of the P in runoff, respectively. Strips of varying widths have been shown to remove from 22 to 89% of TP in runoff (Sharpley et al., 1992; Patty et al., 1997; Schmitt et al., 1999).

Another reason that may be causing observed differences in TP loss among the watersheds is that ground water and surface runoff during a large precipitation event can cross topographically defined catchment boundaries, so the collection area of the runoff becomes uncertain (Garrison et al., 1987). The west and center watersheds, which have road boundaries on the west and south sides, respectively, in addition to topographic boundaries, could have experienced this additional source of surface runoff during large rainfall events.

Table 2. Watershed characteristics and selected soil properties of the three watersheds.

	Watershed		
Property	**East**	**Center**	**West**
Area, ha	**1.65**	**4.44**	**3.16**
Total slope length, m	**234**	**425**	**383**
Watershed slope steepness, %	**2.1**	**1.3**	**0.9**
Steepness of the lowest 100 m, %	**3**	**2**	**1.75**
Length of the grass waterway, m	**102**	**151**	**104**
Ratio of waterway length to total length	**0.44**	**0.35**	**0.27**
Depth to the claypan, cm			
Upper third	**32**	**23**	**35**
Middle third	**35**	**22**	**43**
Lower third	**22**	**20**	**34**
Grass waterway	**49**	**62**	**57**
Soil organic carbon, %†	**2.60**	**2.23**	**1.93**
Soil pH$_{(water)}$†	**6.7**	**6.8**	**7.3**
Clay, %†	**23.4**	**23.4**	**26.2**
Textural class†	**silt loam**	**silt loam**	**silt loam**
Soil test P, kg ha^{-1}	**54**	**52**	**47**

† Ap horizon.

Crop Rotation, Fallow Period, and Total Phosphorus Loss

During the 7-yr study, the watersheds were planted to corn for 3 yr and to soybean for 4 yr (Table 1, Fig. 3). Average annual watershed losses were 1.70 and 1.10 kg TP ha^{-1} during corn and soybean years, respectively. Higher average annual loss of TP during corn years compared with soybean years could be because P fertilizer is more often applied to corn and not to soybeans. However, in this study, P fertilizer was applied to corn only in 1993. During the corn year of 1993, watersheds also received 42% more precipitation than the long-term mean causing higher losses of TP in runoff (Fig. 3). The average annual corn and soybean TP losses over the duration of the experiment (excluding 1993) were 1.12 and 1.10 kg ha^{-1} yr^{-1}, respectively.

The annual TP losses during crop and fallow periods were different among years (Fig. 3). Approximately 48 to 100% of the annual total loss occurred when the ground was free of crops. During the 7-yr study, 34.4 to 66% of the annual precipitation occurred during the fallow period with a 55% mean for the 7-yr study period (Fig. 2). The study was initiated in April 1991 and the reported entire loss for 1991 occurred after the crop was harvested. In contrast, most of the TP loss occurred within the cropping period during the high rainfall year of 1993 (Fig. 2 and 3). However, in all other years, a higher proportion of the TP losses occurred during the fallow periods (Fig. 3). For example, in 1995, when rain continued for several weeks during the corn planting period, the preplanting period loss alone accounted for 89% of the total annual TP loss.

Another possible reason for the higher TP loss during the fallow periods is that the high clay content of the subsoil in these watersheds restricts vertical soil water percolation (Jamison and Peters, 1967). Due to this low permeability, argillic horizons act as a barrier directing the vertical flow horizontally above the clay pan (Blanco-Canqui et al., 2002). At the Midwest Research Claypan Farm near Kingdom City, MO, Blanco-Canqui et al. (2002) observed that approximately 98.5% of applied water in the upper end of the monolith moved laterally through the soil layer above the restrictive argillic horizon after 48 h. These clay soils produce a large volume of surface runoff during periods of saturation in the spring and early summer, especially when the soil is free of any vegetation. A comparison of TP losses in 1993 and 1995 supports the finding that restrictive layer and the amount of precipitation together were the main contributing factors for the TP loss on these watersheds, especially during the fallow period. In a year such as 1995, when rain occurred more frequently, antecedent soil moisture conditions may have been higher than in a normal year. A laboratory study showed that antecedent soil moisture condition affects P loss (McDowell and Sharpley, 2002). Higher antecedent soil moisture conditions also may have contributed to greater TP losses when rain occurred more frequently.

Results of this study suggest that crop cover may have substantially reduced the TP loss from the three row-crop watersheds in 1993, in spite of 42% more rainfall than the long-term mean. At the Claypan Experimental Farm in Missouri, Ghidey and Alberts (1998) showed that fallow-period soil loss was five times higher than during the cropping period under continuous corn or soybean. The observed difference in TP loss during the crop and fallow periods may result from less interaction of runoff with surface soil due to the effects of greater vegetative cover during the crop period (Sharpley et al., 1996).

Runoff Characteristics and Total Phosphorus Loss

Runoff volume and TP loss were highly significant for the three watersheds (r^2 = 0.64–0.73, $p \leq 0.001$; Fig. 4). Runoff in the east watershed had the best relationship with TP loss (r^2 = 0.73; Fig. 4A) while the west watershed had the weakest relationship (r^2 = 0.64; Fig. 4C). However, slopes between TP loss and runoff relationships among the watersheds were not significantly different ($p \leq 0.05$). The slopes of the regression lines for center and west watersheds were the same (0.0006) while the east watershed had a slightly smaller slope (0.0004) (Fig. 4). Figure 4 also shows that the relationship between runoff and TP loss was largely determined by a larger number of small runoff events and only a small number of larger events that occurred during the 7-yr measurement period.

The largest five runoff events averaged over the three watersheds removed a total concentration of 2.63 kg TP ha^{-1} and accounted for 27% of the total loss during the study period. On average, the other 61 runoff events removed 6.87 kg TP ha^{-1} from watersheds. Storm ranking was based on TP loss measured on individual events rather than on total rainfall. Runoff volume varies with rainfall and season. In general, heavy rainfall caused a brief initial high rate of discharge that was an important fraction of the total discharge. These runoff events remove several magnitudes more TP than the small events. Morgan et al. (1986) showed that two or three runoff events each year were responsible for substantial annual soil loss in Mid Bedfordshire in the United Kingdom. The same pattern has been observed in the United States (Edwards and Owens, 1991) and Nigeria (Lal, 1976). The results of this study also show that individual weather years, such as 1993 and 1995, which generated larger runoff volumes, account for a high proportion of total TP losses, depending on antecedent soil moisture condition and the characteristics of the precipitation, such as frequency, intensity, and quantity of the annual precipitation.

The largest five runoff events had an average concentration of 0.93 mg TP L^{-1} as compared with the mean (0.87 mg L^{-1}) for the entire study period (Fig. 5). The mean of the largest five events and the grand mean without the largest five events (0.86 mg L^{-1}) were not significantly different ($p \leq 0.05$). The more frequently occurring small runoff events account for a larger portion (73% of the total) of the TP loss compared with the infrequent large events. Although infrequent larger events remove proportionately larger quantities of P from row-crop agriculture, more frequent small events cumulatively remove larger quantities over an extended period of time. Our study shows that the mean concentration of TP in larger runoff events was not significantly different, but due to the larger runoff volume, proportionately larger amounts of TP were removed from the three watersheds. For the purpose of water quality protection, the USEPA has recommended a maximum level of 0.1 mg TP L^{-1} in surface runoff water (Daniel et al., 1998). Total phosphorus concentrations in runoff from this study's watersheds were consistently greater than the critical value established by the USEPA.

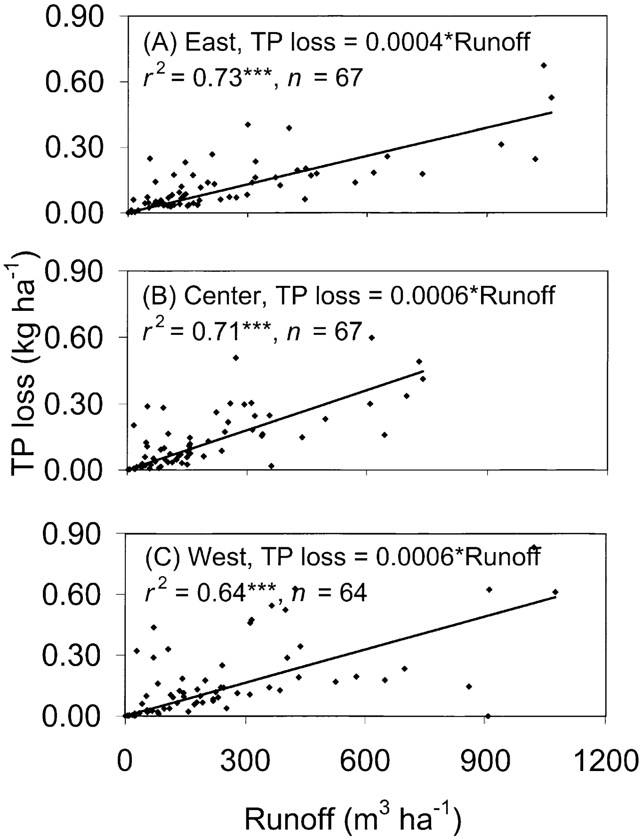

Fig. 4. Relationships between runoff volume and total phosphorus loss for (A) east, (B) center, and (C) west watersheds. * Significant at the 0.001 probability level.**

Events that continued over extended periods of time removed more TP from the study watersheds than short runoff events. Runoff duration explained 61 (east), 39 (center), and 33% (west) of the variation in TP loss (Table 3). The combined data set for all three watersheds showed that duration accounted for 49% ($p \leq 0.001$) of the variation in TP loss. Larger flow events appeared to be responsible for removing significant amounts of TP from row-crop agriculture in the study watersheds. Maximum flow height explained 57 to 75% of the variation in TP loss (Table 3). Both the east and west watersheds had similar r^2 (0.75 and 0.74, $p \leq 0.001$) while the r^2 for the center watershed was only 0.57 ($p \leq 0.01$). In the combined data set, the maximum flow height explained 66% of the variation in TP loss from the three watersheds.

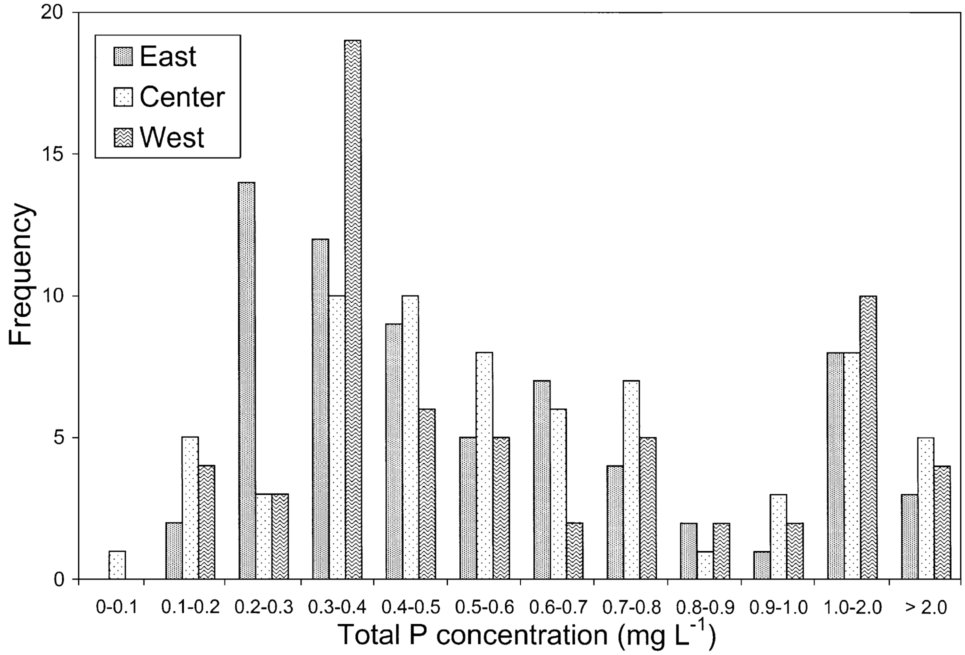

Fig. 5. Total phosphorus concentration and its frequency for the east, center, and west watersheds from 1991 to 1997.

Quinton et al. (2001) showed that TP concentration increased with peak discharge. They suggested that finer soil particles are removed initially and then larger events subsequently remove the coarser surface and the P-rich material underneath. Results of our study support these previous findings as the three watersheds experienced greater losses of TP with increasing runoff volumes.

Sediment and Total Phosphorus Loss

Total P and sediment loss relationships were significant and explained 47 to 58% of the variation in TP loss by sediment (Fig. 6). The west watershed had the weakest relationship ($r^2 = 0.47$, $p \leq 0.001$) among the three watersheds (Fig. 6C). The sediment loss on the east ($r^2 = 0.56$, $p \leq 0.001$) and center ($r^2 = 0.58$, $p \leq 0.001$) watersheds explained more than 56% of the variation in TP loss (Fig. 6A and 6B). The three watersheds had a similar pattern for TP and sediment loss. All three watersheds had a larger number of events with small amounts of TP and sediment loss and a smaller number of events with large amounts of TP and sediment losses. Therefore, we combined the data from the three watersheds to observe the relationship between TP and sediment loss. In the combined data set with 193 observation pairs, sediment loss explained 55% ($p \leq 0.001$) of the variation in TP loss. It is clear that one way to reduce TP loss in runoff is to reduce the sediment loss in runoff. The control of sediment loss is more effective to reduce P in runoff as sediment loss is more related to TP loss than soil test P concentration (Daverede et al., 2003).

Table 3. Linear relationships between total phosphorus (TP) loss, runoff duration, and maximum flow height for the three watersheds from 1995 to 1997.

Watershed	Regression equation	Number of events	Coefficient of determination (r^2)
	Runoff duration		
East	TP loss = 0.005 × duration	12	0.61**
Center	TP loss = 0.004 × duration	12	0.39*
West	TP loss = 0.031 × duration	12	0.47**
Overall	TP loss = 0.004 × duration	36	0.49***
	Maximum flow height		
East	TP loss = 0.007 × height	12	0.75***
Center	TP loss = 0.005 × height	12	0.57***
West	TP loss = 0.007 × height	12	0.74***
Overall	TP loss = 0.006 × height	36	0.66***

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.

Our results support previous findings that sediment and TP loss are highly correlated (Vighi et al., 1991; Eghball and Gilley, 2001). In this study, runoff water from the watersheds passed through grass waterways before the runoff was collected and, therefore, some TP and sediment were possibly removed. Other researchers have observed that grass filter strips remove sediment and P by diffusing surface flow, increasing infiltration, and trapping sediment (Dillaha et al., 1989; Schmitt et al., 1999). These watersheds were in no-till with corn–soybean rotations, and therefore, addition of residue and reduced disturbance of the soil surface may also have affected TP loss in runoff.

Wall et al. (1996) showed that smaller events could carry proportionately more P than larger events as small events remove more clay-size particles with higher amounts of attached P than contained by larger soil particles. Studying soil and P loss on soil trays, McDowell and Sharpley (2003) noticed that more P was lost in soil during the first 30 min of flow than the second 30 min due to selective erosion of finer particles. Our results showed that smaller events removed P at an increasing rate followed by a decreasing rate. The results show that up to a certain sediment loss, TP loss increased at an increasing rate, possibly due to the removal of P-enriched

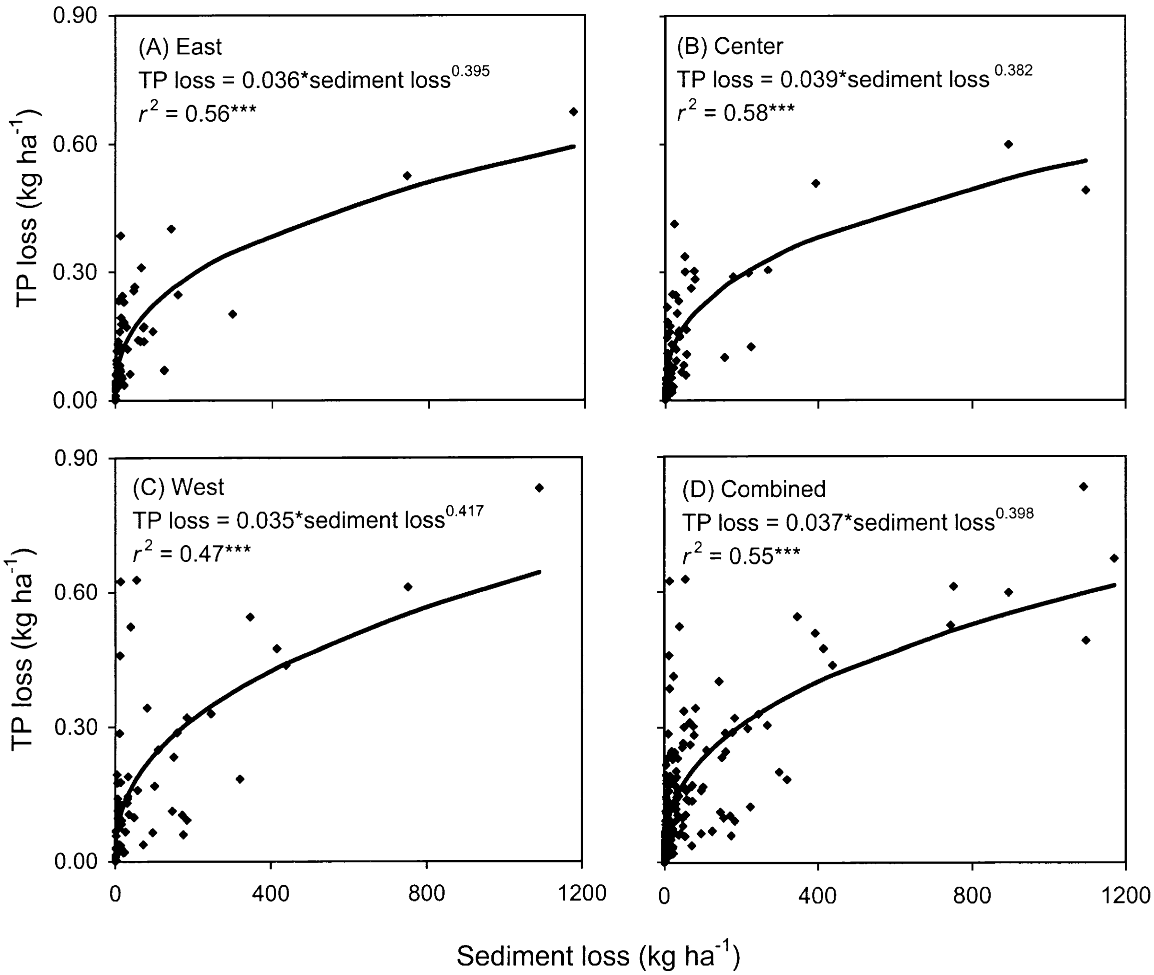

Fig. 6. Relationships between sediment loss and total phosphorus loss for (A) east, (B) center, (C) west watersheds, and (D) all three combined. * Significant at the 0.001 probability level.**

surface soils. As sediment loss continues to increase subsequent runoff events removed soils with less P. Therefore, larger events did not remove P at the same rate. Conversely, when runoff events remove larger suspended loads during high flow, the suspended soils are characterized by a wide range of particles. The phenomenon is supported by the TP concentration data as the concentrations between the largest events and the whole study were not significantly different.

The suspended sediment and TP loss ranged from 0.023 to 1171 kg ha^{-1} and 0 to 0.832 kg ha^{-1}, respectively, during the 7-yr study across the three watersheds. The mean TP concentration for losses in sediment <10 kg ha^{-1} was 0.06 kg TP ha^{-1}, which was significantly ($p \leq 0.01$) smaller than the mean TP concentration (0.32 kg TP ha^{-1}) of sediment >100 kg ha^{-1} (Table 4). During the 7-yr study, the runoff events with the largest five sediment losses accounted for 24% of the 7-yr TP loss. Figures 4 and 6 show that small events are more prevalent than larger events, so the greater frequency of smaller events leads to higher cumulative P losses than for larger events.

CONCLUSIONS

The results of this study emphasize the complex and dynamic nature of the variety of controlling factors affecting P loss from watersheds with row-crop agriculture. Variations in landscape, soil properties, weather conditions, and changes in agricultural management practices over time affect surface P losses in runoff. This study indicates that the average total P losses over a 7-yr

Table 4. Mean sediment and total phosphorus loss for the three watersheds from 1991 to 1997, for all events, sediment loss < 10 kg ha^{-1}, sediment loss > 100 kg ha^{-1}, and for the five largest sediment losses.

	All events			Sediment loss < 10 kg ha^{-1}			Sediment loss > 100 kg ha^{-1}			Largest five events	
Watershed	*n*	Sediment	P	*n*	Sediment	P	*n*	Sediment	P	Sediment	P
		kg ha^{-1}			kg ha^{-1}			kg ha^{-1}		kg ha^{-1}	
East	67	58.7	0.125	31	4.37	0.055	7	395.7	0.313	502.9	0.460
Center	67	69.3	0.133	29	3.90	0.052	8	428.8	0.339	575.8	0.469
West	64	95.5	0.175	21	4.07	0.068	16	312.1	0.315	608.5	0.648

period generally differed from losses reported for other watersheds without the presence of claypan soils. Possible factors affecting observed P losses and concentration in this study were the presence of grass waterways at the base of all three watersheds, the use of no-till, and the practice of following a corn–soybean crop rotation that reduced P fertilizer applications, especially during years in which soybeans were grown. Differences in observed P losses among the three adjacent watersheds over the 7-yr period were possibly caused by differences in the relative proportion of the watershed lengths occupied by grass waterways and the possible effects of the breaching of catchment boundaries during large rainfall events.

Runoff volume, maximum flow rate, runoff duration, and the presence of vegetative ground cover were the main factors that affected P loss in the three watersheds from individual runoff events. Above-average precipitation, especially when it occurred within a 2- or 3-mo period, caused the greatest observed losses of total P in runoff. The highest TP losses most often occurred during fallow periods before crops were planted and after they had been harvested. Decreasing runoff volume and flow rate and extending the period of vegetative cover through changes in agricultural conservation practices may be the most effective long-term strategies to reduce P losses from agricultural watersheds in the claypan region.

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