Effect of Rainfall Simulator and Plot Scale on Overland Flow and Phosphorus Transport

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ABSTRACT

Rainfall simulation experiments are widely used to study erosion and contaminant transport in overland flow. We investigated the use of two rainfall simulators designed to rain on 2-m-long (2-m^2) and 10.7-m-long (32.6-m^2) plots to estimate overland flow and phosphorus (P) transport in comparison with watershed-scale data. Simulated rainfall (75 mm h^{-1}) generated more overland flow from 2-m-long (20 L m^2) than from 10.7-m-long (10 L m^2) plots established in grass, no-till corn (*Zea mays* L.), and recently tilled fields, because a relatively greater area of the smaller plots became saturated (>75% of area) during rainfall compared with large plots (<75% area). Although average concentrations of dissolved reactive phosphorus (DRP) in overland flow were greater from 2-m-long (0.50 mg L^{-1}) than 10.7-m-long (0.35 mg L^{-1}) plots, the relationship between DRP and Mehlich-3 soil P (as defined by regression slope) was similar for both plots and for published watershed data (0.0022 for grassed, 0.0036 for no-till, and 0.0112 for tilled sites). Conversely, sediment, particulate phosphorus (PP), and total phosphorus (TP) concentrations and selective transport of soil fines (<2 μm) were significantly lower from 2- than 10.7-m-long plots. However, slopes of the logarithmic regression between P enrichment ratio and sediment discharge were similar (0.281–0.301) for 2- and 10.7-m-long plots, and published watershed data. While concentrations and loads of P change with plot scales, processes governing DRP and PP transport in overland flow are consistent, supporting the limited use of small plots and rainfall simulators to assess the relationship between soil P and overland flow P as a function of soil type and management.

Phosphorus is an essential nutrient for crop and animal production that can also accelerate freshwater eutrophication (Carpenter et al., 1998; Sharpley, 2000). In the USA, eutrophication is one of the most widespread water quality impairments (USEPA, 1996), with agriculture a primary source of P in the surface waters of many watersheds (United States Geological Survey, 1999). Concern over eutrophication has prompted most states to develop recommendations for land application of P and watershed management based on the potential for P loss in overland flow (USDA and USEPA, 1999). As part of these recommendations, states are assigning soil P thresholds above which the potential for dissolved P loss in overland flow becomes unacceptable. These environmental thresholds are used in site assessment indices to identify agricultural fields that are most susceptible to soil P loss and indicate when current management should be reevaluated (Sharpley et al., 2003).

Despite the widespread implementation of P-based management strategies across the USA, limited field information exists on which to base environmental thresholds of soil P. Consequently, the National Phosphorus Research Project (NPRP) was launched to assess the effects of soil properties, particularly soil test P level, and management on P loss in overland flow (Sharpley et al., 2002b). The NPRP is composed of a consortium of federal and state agencies, as well as land grant universities, representing more than 20 states. To expedite data collection, promote comparability of results, and attempt to maintain field relevancy, studies are conducted on an in situ basis using paired, 2-m^2 runoff plots with 2-m flow-path length. Overland flow from the NPRP plots is generated by a portable rainfall simulator based on the operating designs of Shelton et al. (1985) and Miller (1987) and described by Humphry et al. (2002).

In the early 1990s, the Water Erosion Prediction Project (WEPP) used a rotating-boom rainfall simulator (15.2-m-diameter boom) to update soil loss factors in the Universal Soil Loss Equation (USLE) and to improve erosion prediction technology (Simanton and Renard, 1992). Two 36.2-m^2 plots with 10.7-m flow-path length are used with the WEPP simulator. The raindrop size, energy, distribution uniformity, and intensities of both NPRP and WEPP simulators have undergone extensive testing and comparison with the properties of natural rainfall (Humphry et al., 2002; Simanton and Renard, 1992). Both NPRP and WEPP simulators use the same nozzles and water pressure to produce rainfall of comparable characteristics.

To date, little research exists on the effect of plot scale on P transport in overland flow. There is, however, a growing body of research on scale-related trends in hydrology and erosion that is relevant to P transport. Wauchope and Burgoa (1995), reviewing pesticide-related research, observed that runoff volume per unit area decreased with increasing plot size, while the length of rainfall required to initiate overland flow increased. Bloschl and Sivapalan (1995), reviewing hydrologic literature, hypothesized that as slope length increases, overland flow processes change from infiltration excess processes to saturation excesses. Le Bissonnais et al. (1998) noted that the selective erosion of fine particles increased with plot size and length.

The main objective of this research was to compare the effects of two rainfall simulators (i.e., WEPP and NPRP) on overland flow patterns (e.g., time to initiation, volume, discharge rate, peak flow), P concentrations (dissolved and total P), and sediment discharge, in relation to plot size and watershed data. Both simulators rely upon the same rainfall generation system, nozzles,

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Abbreviations: θ, volumetric soil moisture; DRP, dissolved reactive phosphorus; NPRP, National Phosphorus Research Project; PER, phosphorus enrichment ratio; PP, particulate phosphorus; TP, total phosphorus; WEPP, Water Erosion Potential Predictor.

and intensity (75 mm h^{-1}), although plot length (2 m) and area (2 m^2) of the NPRP simulator is much less than that of the WEPP simulator (10.7 m and 32.7 m^2, respectively). Assuming the WEPP rainfall simulator represents field-scale processes reasonably well, due to its large size and history of extensive testing, we attempted to determine if the more portable NPRP simulator can accurately represent overland flow–rainfall interaction, soil P–overland flow extraction, P transport processes, and sediment discharge. An additional objective of this study was to establish the impact of scale and geometry of rainfall simulators on their use in examining P transport in overland flow.

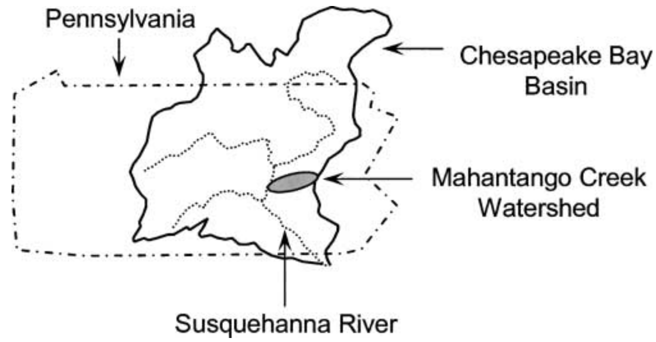

Fig. 1. Location of the study area within the Mahantango Creek watershed in relation to the Susquehanna River and Chesapeake Bay watershed.

MATERIALS AND METHODS

Study Area and Management

Simulated rainfall studies were conducted within the mixed land-use watershed, FD-36, a 39.5-ha subwatershed of Mahantango Creek, a tributary to the Susquehanna River and ultimately the Chesapeake Bay (Fig. 1). Three sites in the FD-36 watershed were selected to cover a range in soils, P status, and tillage. The slope of all sites was between 4 and 5%. Sites included a Berks loam (loamy-skeletal, mixed, active, mesic Typic Dystrudept) in orchardgrass (*Dactylis glomerata* L.); a Berks loam that was tilled prior or seeding with orchardgrass; and a Watson clay loam (fine-loamy, mixed, active, mesic Typic Fragiudult) in no-till corn. The tilled site was chisel-plowed to a depth of about 25 cm and disked to prepare seedbed surface before planting orchardgrass in mid-April 2000. Rainfall simulations were conducted during months in which the majority of overland flow naturally occurs (April and May; Pionke et al., 2000). At the tilled site, simulations were conducted one week after plowing, in late April 2000. Simulations at the grassed Berks and no-till Watson sites (before corn planting) were conducted in early May 2001.

At each site, duplicate adjacent overland flow plots were established for each simulator. Both NPRP and WEPP rainfall simulations were conducted at the same time and on the same day (Fig. 2).

National Phosphorus Research Project Rainfall Simulator Protocol

Overland flow plots, each 1 by 2 m, with the long axis orientated down the slope, were delineated by metal borders installed 5 cm above and below ground level to isolate overland flow. Rainfall was applied with one TeeJet 2HH-SS50WSQ nozzle (Spraying Systems Co., Wheaton, IL) approximately 2.5 m above the soil to achieve terminal velocity (Sharpley et al., 2002b). The nozzle, associated plumbing, in-line filter, pressure gauge, and electrical wiring are mounted on a 3- by 3- by 3-m aluminum frame fitted with canvas walls to provide a windscreen. A coefficient of uniformity of >85% was obtained for rainfall over a 4-m^2 footprint, which encompasses one pair of abutting plots. An average rainfall intensity of 75 mm h^{-1} was applied until 30 min of runoff was obtained. This rainfall intensity and duration has an approximate 10-yr return frequency in south-central Pennsylvania. Local ground water was used as the water source for the simulator and had a DRP concentration of <0.01 mg L^{-1}, total phosphorus (TP)

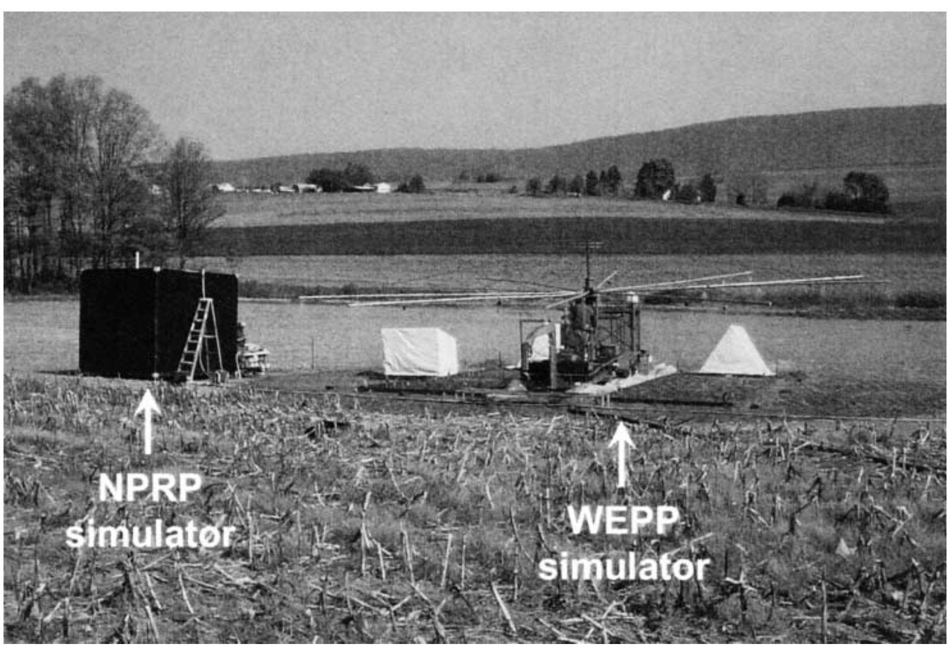

Fig. 2. Simultaneous National Phosphorus Research Project (NPRP) and Water Erosion Potential Predictor (WEPP) rainfall simulations on the no-till Berks soil.

of 0.02 mg L^{-1}, nitrate N of 3.1 mg L^{-1}, pH of 5.7, and electrical conductivity of 0.02 S m^{-1}. Electrical conductivity measurements were made using a digital conductivity meter. Before rainfall, volumetric soil moisture (θ) was determined using a capacitance sensor at five locations within a plot (Theta Probe; Delta-T Devices, Cambridge, UK).

Two simulated rainfalls, each of 75 mm h^{-1} for 30 min of runoff, were applied on consecutive days coinciding with WEPP simulations. Overland flow was collected in metal gutters at the downslope edge of each plot and pumped to 200-L plastic containers. Total overland flow was measured by weighing the containers. A runoff sample was collected from each container after thorough agitation to resuspend and mix sediments.

Water Erosion Prediction Project Rainfall Simulator Protocol

The WEPP simulator is trailer-mounted, with 10 rotating booms (each 7.6 m long) radiating from a central center of rotation, which rotate at about 4 rpm (Simanton and Renard, 1992) (Fig. 2 and 3). The arms support 30 TeeJet 2HH-SS50WSQ nozzles positioned at various distances from the stem. The nozzles spray downward from an average height of 2.4 m, apply rainfall at an average intensity of 75 mm h^{-1}, and produce drop-size distributions similar to natural rainfall. Simulator energies are about 77% of those of natural rainfall and the simulator produces intermittent rainfall impulses at the plot surface as the booms pass over the plot. The spatial distribution of rainfall over each plot has a coefficient of uniformity of >90%. Changes in rainfall intensities are produced by regulating the number of open nozzles: 15 nozzles are used to achieve an intensity of 75 mm h^{-1}. Two plots, 3.05 by 10.7 m (32.6 m^2), were covered by the simulator (Fig. 3). Before rainfall, θ was determined by a capacitance sensor at 15 locations within each plot.

Two rainfall simulation runs were made on each plot pair on consecutive days. Rainfall application rate was measured with a recording rain gauge and rainfall distribution on each plot measured with six nonrecording rain gauges. Plot overland flow was measured by precalibrated 0.12-m HS flumes (4 L s^{-1} maximum capacity) equipped with water-level recorders, designed to measure small flows with a high degree of accuracy (<1% error; Brakensiek et al., 1979). Continuous hydrographs were produced using the flume's depth–discharge rating table. During a run, times of ponding (half of the plot surface had standing water), runoff initiation, sediment samples, and end of runoff were recorded on field notes for later comparison with recorder charts. Although overland flow samples were collected at 5-min intervals starting 2.5 min after flow initiation, data in this paper reflect composite samples (flow-weighted) of bulked flow to enable direct comparison with NPRP simulator results.

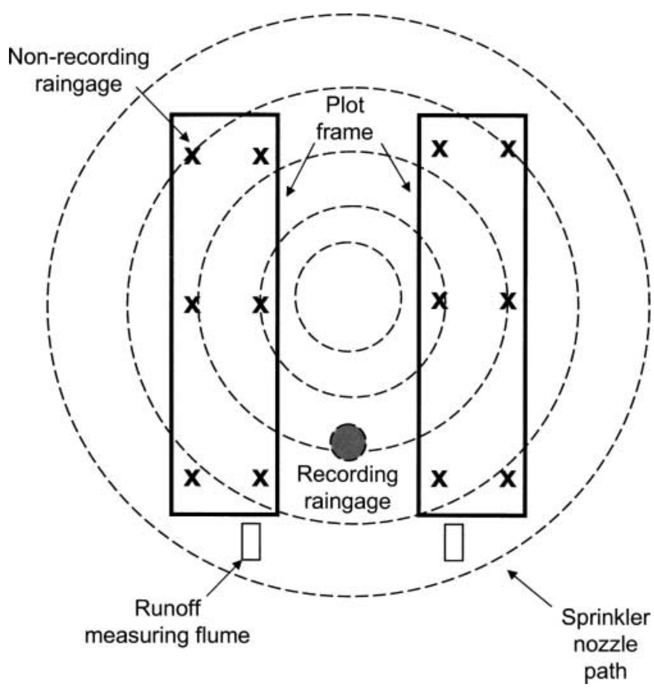

Fig. 3. Plot layout for Water Erosion Potential Predictor (WEPP) rainfall simulations.

Chemical Analyses

After both WEPP and NPRP rainfall simulations, a minimum of 10 soil samples (0–5 cm) was collected within each plot, composited, air-dried, sieved (2 mm), and stored for physical and chemical analysis. For all runoff samples, a subsample was immediately filtered (0.45 μm) and stored at 277 K. Filtered samples were analyzed within 24 h of collection and unfiltered samples no more than 7 d after the completion of the rainfall simulation.

Soil particle size analysis was conducted by the hydrometer method after dispersion with sodium hexametaphosphate (Day, 1965). Organic C was determined by combustion using a LECO (St. Joseph, MI) C/N analyzer and pH using a glass electrode at a 1:2.5 soil to water ratio (w/w). Mehlich-3 soil P concentration was determined by 5 min of end-over-end extraction of 1 g soil with 10 mL mixture of 0.2 M CH_3COOH, 0.25 M NH_4NO_3, 0.015 M NH_4F, 0.013 M HNO_3, and 0.001 M EDTA (Mehlich, 1984). Total soil P was determined following digestion with a semimicro Kjeldahl procedure (Bremner, 1996).

The concentration of DRP (subsequently referred to as DRP) in overland flow was determined on the 0.45-μm filtered sample. The concentrations of both total dissolved phosphorus (TDP) and TP were determined on filtered and unfiltered runoff samples, respectively, following digestion with a semimicro Kjeldahl procedure (Bremner, 1996). Particulate phosphorus (PP) was calculated as the difference between TP and TDP. Phosphorus in all soil extracts, filtrates, and neutralized digests was measured by the colorimetric method of Murphy and Riley (1962).

The suspended sediment concentration of each overland flow event was measured in duplicate as the difference in weight of 250-mL aliquots of unfiltered and filtered (0.45 μm) runoff samples after evaporation (378 K) to dryness.

Statistical Analyses

Comparisons of overland flow properties between simulators were conducted by Student's t test, while comparisons between soils were conducted by analysis of variance (ANOVA). Least squares regression was used to describe associations between individual variables, with all reported r^2 values significant at the 0.05 probability level. Differences between regression coefficients or slopes of any two regressions ($P <$ 0.05) were determined by testing the homogeneity of regression coefficients (Gomez and Gomez, 1984). All analyses were performed with SPSS Version 10.0 (SPSS, 1999).

RESULTS AND DISCUSSION

Physical and chemical properties of the grassed and tilled Berks soils were generally similar across plots,

Table 1. Mean and range (in parentheses) values of physical and chemical properties of the Berks and Watson soils.

Parameter	Berks, grassed	Berks, tilled	Watson, no-till
pH	5.8 (5.6–6.1)	5.9 (5.6–6.2)	6.8 (6.5–7.0)
Clay, %	22 (19–25)	24 (18–26)	35 (31–37)
Organic C, g kg^{-1}	16.6 (9–23)	13.7 (7–21)	25.2 (16–34)
Mehlich-3 P, mg kg^{-1}	214 (44–402)	229 (63–411)	174 (58–331)
Total P, mg kg^{-1}	735 (348–1256)	817 (449–1208)	648 (336–953)

while the no-till Watson soils had higher pH, clay, and organic C (Table 1). Mehlich-3 P and total P concentrations of all soils ranged widely, reflecting differences in manure application history; P concentrations in Berks soils were generally higher than in Watson soils.

Overland Flow Response

Response time between start of rainfall and initiation of overland flow was similar for the NPRP and WEPP simulators across all sites (Table 2). In addition, temporal trends in overland flow were consistent across soils for both simulators; it took appreciably longer for overland flow to occur and in lower volumes from the coarser-textured Berks soil than from the Watson soil. Differences in overland flow response time reflect the greater permeability of the Berks soil (15 to 150 mm h^{-1}) than the Watson soil (1.5 to 15 mm h^{-1}) (Eckenrode, 1985), as well as the influence of vegetative cover and tillage management on infiltration (Nash et al., 2002). For both simulators, overland flow occurred more rapidly after the start of rainfall on Day 2 than on Day 1 (Table 2), as soil moisture before rainfall was greater on Day 2 than Day 1. On the grassed Berks soil, θ before rainfall increased from 28% on Day 1 to 39% on Day 2, while θ before rainfall increased from 40 to 50% on the no-till Watson soil and from 23 to 35% on the tilled Berks soil. The standard error of θ was consistently less than $\pm 2\%$ of mean values for each plot.

Total overland flow volume per unit area (L m^{-2}) and peak flow rates per unit area (L m^{-2} min^{-1}) were significantly greater under the NPRP simulator than under the WEPP simulator (Table 2). These differences suggest varying source areas of overland flow between the two plot scales. One possibility is that overland flow tends to be produced at the lower end of the plots, where subsurface lateral flow accumulates. For instance, given the low slope gradient, subsurface lateral flow may be intercepted by the lower plot boundary. As that water accumulates in the surface soil of the lower plot area, "infiltration" or "saturation excess" overland flow, as described by Nash et al. (2002), ensues. Under this process of overland flow generation, areas producing overland flow would be expected to expand upslope as rainfall continues.

A variety of observations support a variable source area hypothesis of overland flow generation. Both Berks and Watson soils in this study possess prominent plow pans that may impede vertical infiltration below the surface horizon and promote a component of lateral subsurface flow (Kleinman et al., 2003). Comparison of representative unit-width hydrographs (i.e., hydrographs normalized on a 1-m width basis) shows that flow from NPRP and WEPP plots increases at approximately the same rate (Fig. 4). In this case, flow from the NPRP plot plateaus with roughly 100% of rainfall converted to overland flow, while flow from the WEPP plot continues to rise for approximately 10 min, consistent with the expansion of the overland flow–producing zone beyond a 2-m flow path.

If overland flow occurred uniformly across the entire plot area, then different overland flow response times and hydrograph characteristics would be expected between the NPRP and WEPP simulators (Dingman, 1994). Assuming that overland flow is a function of saturated areas within the plots (i.e., saturation excess overland flow), unit area maximum flow rates indicate that 22 to 66% of the WEPP plot area was contributing overland flow, in comparison with 73 to 100% for the NPRP plots.

Table 2. Overland flow response to rainfall produced by the National Phosphorus Research Project (NPRP) (2-m^2 plots) and Water Erosion Potential Predictor (WEPP) (32.6-m^2 plots) simulators, both using an intensity of 75 mm h^{-1} for 30 min of overland flow. Data presented are averages for all plots on each soil and management type.

Parameter	Day 1		Day 2	
	NPRP	WEPP	NPRP	WEPP
		Berks, grassed		
Response time, min	15.0 (2.3)a†	18.0 (2.7)a	6.0 (2.4)b	9.0 (2.5)b
Flow, L m^{-2}	17.3 (1.7)a	6.4 (1.0)b	23.6 (1.3)c	8.7 (0.9)d
Peak flow rate, L m^{-2} min^{-1}	0.91 (0.09)a	0.27 (0.05)b	1.18 (0.08)c	0.43 (0.06)d
		Berks, tilled		
Response time, min	22.0 (2.8)a	23.0 (3.6)b	9.0 (2.8)c	8.0 (3.3)c
Flow, L m^{-2}	24.4 (1.6)a	13.3 (1.2)b	29.2 (1.6)c	16.6 (1.4)d
Peak flow rate, L m^{-2} min^{-1}	1.27 (0.21)a	0.74 (0.08)b	1.46 (0.16)a	0.82 (0.08)b
		Watson, no-till		
Response time, min	4.0 (0.6)a	2.5 (0.7)a	1.0 (0.3)b	0.5 (0.4)b
Flow, L m^{-2}	22.0 (2.0)a	11.2 (1.1)b	27.2 (1.6)c	14.9 (1.4)d
Peak flow rate, L m^{-2} min^{-1}	1.03 (0.11)a	0.60 (0.08)b	1.12 (0.09)a	0.68 (0.05)b

† Values followed by the same letters are not statistically different ($P < 0.05$) between simulator types and day of rainfall as determined by analysis of variance for all data from each soil and management type (i.e., grassed Berks, tilled Berks, and no-till Watson). Numbers in parentheses represent ±standard errors of the mean values.

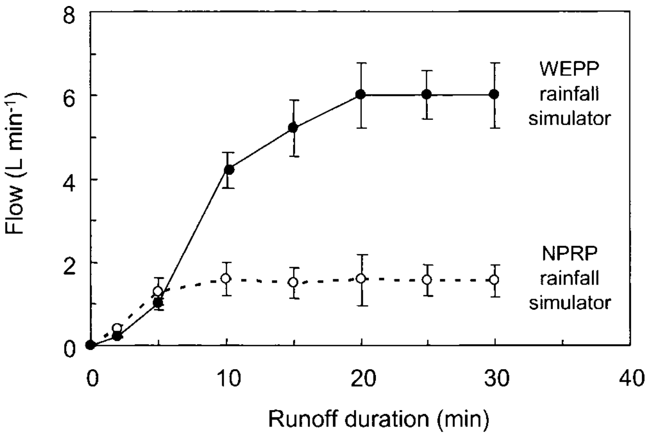

Fig. 4. Unit width hydrographs for National Phosphorus Research Project (NPRP) and Water Erosion Potential Predictor (WEPP) simulators for the first day of rainfall on the no-till Watson soil. Hydrographs are normalized on a 1-m-width basis for comparison. Bars represent standard errors of the mean values.

Spatial variability in surface soil infiltration properties may also contribute to the lower unit area overland flow from WEPP plots. Overland flow generated within the WEPP plots may thus have a greater opportunity to infiltrate in nonsaturated areas than in the fully saturated NPRP plots. Indeed, Srinivasan et al. (2002) observed that overland flow from a Berks soil infiltrated within several meters of its origin. The apparent plateau of flow from the WEPP plot at a rate representing less than 75% of incoming rainfall (Fig. 4) suggests that there is a greater potential for infiltration in the larger WEPP than NPRP plots.

Observed differences in overland flow volume between plot scales run contrary to the findings of Gascho et al. (1998), who found no significant difference between 6-m^2 (3-m-long) and 622-m^2 (43-m-long) plots under simulated rainfall. Soils studied by Gascho et al. (1998) were loamy sand, as opposed to silt loam and clay loam textures of the Berks and Watson soils, respectively. These loamy sands were also crust-forming soils, which may not promote near-surface lateral flow, a key process controlling variable source area hydrology. Results of that study may also reflect greater homogeneity of soil infiltration properties than in this study. For instance, the lower rainfall intensity (25 mm h^{-1}) and longer rainfall periods (2 h) in Gascho et al. (1998) may have contributed to more uniform soil moisture distribution within plots.

Phosphorus Transport

Dissolved reactive P concentration of overland flow was significantly greater with the NPRP simulator than with the WEPP simulator (Table 3). For both simulators, DRP concentrations were lower on Day 2 than on Day 1, probably due to a temporary dilution of the pool of P that is released to overland flow in the interacting depth of surface soil. While the greater infiltration of rainfall within the WEPP plots may have resulted in greater vertical translocation of soluble P from the effective depth of soil–overland flow interaction, differences

Table 3. Overland flow, P concentration, and sediment discharge from each soil and management type using the National Phosphorus Research Project (NPRP) (2-m flow-path) and Water Erosion Potential Predictor (WEPP) (10.7-m flow-path) rainfall simulator for an intensity of 75 mm h^{-1} for 30 min of overland flow.

	Day 1		Day 2	
Parameter	NPRP	WEPP	NPRP	WEPP
	Berks, grassed (400 mg Mehlich-3 P kg^{-1})			
Dissolved P, mg L^{-1}	0.766a	0.560b	0.445bc	0.335c
Particulate P, mg L^{-1}	1.776a	2.499c	1.226b	1.881a
Total P, mg L^{-1}	2.542a	3.059c	1.671b	2.216d
Sediment, g L^{-1}	1.20a	1.57c	0.68b	1.24a
	Berks, tilled (320 mg Mehlich-3 P kg^{-1})			
Dissolved P, mg L^{-1}	0.304a	0.207b	0.195b	0.148c
Particulate P, mg L^{-1}	2.756a	3.764c	2.054b	2.915a
Total P, mg L^{-1}	3.060a	3.971c	2.249b	3.063a
Sediment, g L^{-1}	3.96a	5.71c	3.17b	5.28c
	Watson, no-till (330 mg Mehlich-3 P kg^{-1})			
Dissolved P, mg L^{-1}	0.438a	0.286b	0.265b	0.175c
Particulate P, mg L^{-1}	1.376a	2.080c	1.164b	1.749d
Total P, mg L^{-1}	1.814a	2.366c	1.429b	1.924a
Sediment, g L^{-1}	2.25a	2.91c	1.63b	2.01a

† Values followed by the same letters are not statistically different ($P < 0.05$) between simulator types and day of rainfall as determined by analysis of variance for all data from each soil and management type (i.e., grassed Berks, tilled Berks, and no-till Watson).

in DRP concentration between simulators cannot be attributed solely to dilution, as overland flow volume was greater with the NPRP than WEPP simulator (Table 2). Rather, significantly lower sediment discharge from the NPRP than WEPP plots (Table 3) probably resulted in a lower readsorption of P by particulates during overland flow (Sharpley et al., 1981; McDowell and Sharpley, 2002). Differences in sediment discharge between NPRP and WEPP plots are consistent with the shorter flow-path length of the NPRP (2 m) than WEPP (10.7 m) plots.

The lower sediment discharge with the NPRP simulator is reflected in significantly lower PP concentrations in overland flow from the NRPR plots (Table 3). Again, it is likely that the longer flow-path length of the WEPP plots caused an increase in overland flow velocity, erosivity, and subsequent entrainment of particulates and associated P relative to the NPRP plots (Table 3). The selective erosion of fine particles also increased with flow-path length (Table 4). For instance, for the grassed Berks soil, sediment eroded from the WEPP plots was comprised of an average 26% clay-sized particles (<2 μm) during Day 1 overland flow, while sediment from the NPRP plots averaged only 19% clay (Table 4). This probably explains the wider PP to DRP ratio in Day 1 overland flow for the WEPP (4.7) than for the NPRP simulator (2.3) (Table 4). Similar enrichments of clay-sized particles and wider PP to DRP ratios were observed for the tilled Berks and no-till Watson soils and during Day 2 overland flow for all sites (Table 4). The difference in PP to DRP ratio results from the fact that P associated with clay-sized particles is less desorbable than P sorbed by sand-sized particles (McDowell et al., 2001).

The effect of flow-path length on PP entrainment in overland flow and the erosional process was evaluated

Table 4. Percent clay-sized material (<2 μm) in eroded sediment and particulate phosphorus (PP) to dissolved reactive phosphorus (DRP) ratio averaged for overland flow from the Berks and Watson sites for the National Phosphorus Research Project (NPRP) and Water Erosion Potential Predictor (WEPP) simulators.

Soil	Clay-sized particles		PP to DRP ratio	
	NPRP	WEPP	NPRP	WEPP
	%			
		Day 1 overland flow		
Berks, grassed	19a†	26b	2.3a	4.7b
Berks, tilled	12a	20b	8.0a	12.4b
Watson, no-till	24a	34b	6.1a	9.9b
		Day 2 overland flow		
Berks, grassed	22a	29b	2.8a	4.2a
Berks, tilled	13a	18a	7.3a	11.7b
Watson, no-till	26a	36b	4.9a	8.5b

† Values followed by the same letters are not statistically different ($P < 0.05$) between simulator types and day of rainfall as determined by analysis of variance for all data from each soil and management type (i.e., grassed Berks, tilled Berks, and no-till Watson).

by calculating the phosphorus enrichment ratio (PER) as the P concentration of sediment discharged (mg PP kg^{-1} sediment) divided by that of source soil (mg TP kg soil^{-1}). The PER was a function of sediment discharge for both NPRP and WEPP simulators (Fig. 5). However, PER at any given sediment discharge was significantly greater ($P < 0.05$) for WEPP than for NPRP plots for each of the soil treatments (grassed Berks and tilled Berks and no-till Watson). This results from the greater selective erosion of clay-sized particles in overland flow from WEPP plots. Although basic differences in WEPP (rotating boom and pulsed rainfall) and NPRP (stationary and continuous rainfall) simulators may have affected particle-size sorting, the data suggest this to be minimal. Even so, analysis of homogeneity of the PER and sediment discharge regression showed that slopes were statistically similar ($P < 0.05$) for NPRP and WEPP plots (Fig. 5). This suggests that although the selective removal of fines was greater at longer flow-path lengths, similar erosion processes governing PP transport in overland flow were operating at both plot scales.

At a much broader scale, Sharpley et al. (1985) calculated PER for up to 50 overland flow events from 2- to 6-ha watersheds in Oklahoma over two years. In that study, slopes of the Ln PER–Ln sediment discharge regression averaged 0.286 for six native grass and six conventionally tilled wheat (*Triticum aestivum* L.) watersheds. In this study, regression slopes were 0.281 and 0.301 for the NPRP and WEPP simulators, respectively.

Relationship between Overland Flow Phosphorus and Soil Phosphorus

The concentration of DRP in overland flow increased with Mehlich-3 P concentration of plot soils, although DRP concentrations were greater from the smaller NPRP than WEPP plots (Fig. 6). Analysis of homogeneity of regression coefficients for the relationship of DRP and Mehlich-3 P showed that absolute values of regression slopes for Berks (grassed and tilled) and Watson

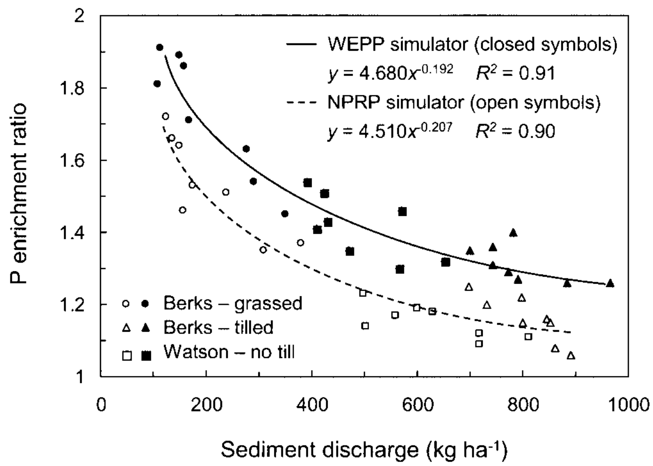

Fig. 5. Relationship between P enrichment ratio and sediment discharge of overland flow generated by the National Phosphorus Research Project (NPRP) and Water Erosion Potential Predictor (WEPP) rainfall simulators for grassed and tilled Berks and no-till Watson soils.

soils were statistically similar ($P < 0.05$) for NPRP and WEPP simulators (Fig. 6). For the grassed and tilled Berks soil, regression slopes using the NPRP simulator (0.0022 and 0.0105) were similar ($P < 0.05$) to those associated with the WEPP simulator (0.0021 and 0.0099). For the Watson soil, slopes were 0.0030 for NPRP and 0.0029 for WEPP simulators (Fig. 6).

The similarity in DRP–Mehlich-3 P regression slopes between NPRP and WEPP simulators suggests that overland flow processes controlling soil P release and transport are independent of simulator type, flow-path length, and plot size. However, differences in DRP concentrations and overland flow volumes between simulators, as reflected by the *y* intercepts of the regression equations (Fig. 6), limits their use in quantifying P loss from agricultural landscapes due to the obvious effects of scale on P loss. This is consistent with NPRP objectives, which are not to quantify P losses as a function of field-scale agricultural management, but to determine factors controlling the relationship between overland flow P and soil P and then define this relationship for a wide range of soils (Sharpley et al., 2002b). Rainfall simulators and small plots cannot reproduce flow process occurring over a landscape or hillslope and as such must be limited to elucidating flow–soil P interdependencies.

Even so, some critical processes controlling overland flow–soil P interdependency appear to be analogous for overland flow generated from rainfall simulators and larger-scale watersheds (Sharpley et al., 2002a). For example, the slopes of the overland flow–Mehlich-3 soil P regression were 0.0027 for ten 2- to 6-ha grassed watersheds and 0.0135 for eight 2- to 3-ha conventionally tilled wheat watersheds in Oklahoma (Sharpley et al., 1991; Smith et al., 1991). In a recent review, Sharpley et al. (2002a) found that regression slopes were lower for 38 grasses (0.0015–0.0035, mean of 0.0022 and standard error of 0.0007) than for no-till (0.0023–0.0044, mean of 0.0036 and standard error of 0.0007) or cultivated watersheds (0.0090–0.0152, mean 0.0112 and standard

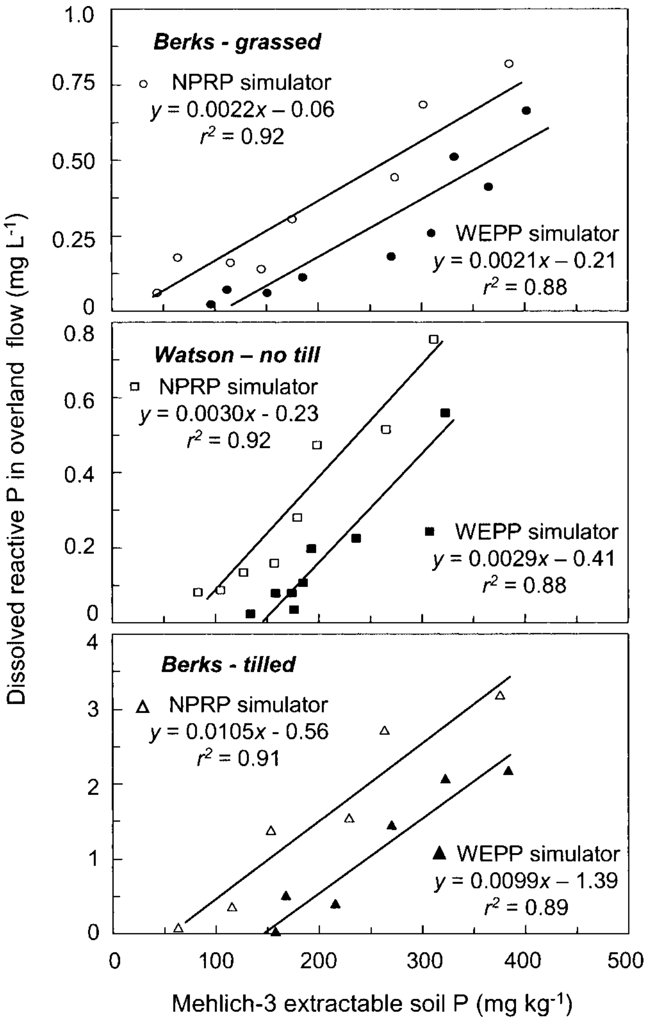

Fig. 6. Relationship between the dissolved reactive P concentration of overland flow generated by the National Phosphorus Research Project (NPRP) and Water Erosion Potential Predictor (WEPP) rainfall simulators for grassed and tilled Berks and no-till Watson soils.

error of 0.0007). These regression slopes and the relative differences between tillage practices are similar to values obtained in this study with NPRP and WEPP simulators for grassed (0.0022 and 0.0021), no-till (0.0030 and 0.0029), and tilled sites (0.0105 and 0.0099) (Fig. 6). The consistency of regression slopes derived from small-plot (<40 m^2) to watershed (>2 ha) scales is evidence that similar soil P release and transport processes operate across these scales.

CONCLUSIONS

Plot length influences hydrology, sediment discharge, and concentration of DRP, PP, and TP in overland flow. Differences in overland flow volume, peak flow, and hydrograph characteristics indicate that a proportionally smaller area of the WEPP plots contributed overland flow, and that infiltration for the WEPP plots was greater under equilibrium conditions than within the NPRP plots. Even so, trends in overland flow over time and between soils were generally consistent for the two simulators.

From the standpoint of water quality, DRP concentrations were consistently greater in overland flow from 2- than 10.7-m-long plots. In contrast, sediment discharge and PP concentrations were lower in overland flow from 2- than 10.7-m-long plots. This suggests that the greater enrichment of clay-sized particles in overland flow from longer plots controls not only the form but the concentration of P in overland flow.

No comparison was made of rainfall simulator and field-scale estimates of overland flow characteristics, P concentration, and sediment discharge, due to a lack of data for natural rainfall and broader scales (e.g., fields, hillslopes) that covered the range of soil P levels and tillage treatments used with the simulators. However, the similarity of overland flow P–soil P relationships derived from plot and watershed-based studies, supports the conclusion that processes controlling P release from soil and transport as DRP are similar for overland flow generated from rainfall simulators and natural rainfall. Comparable PER values for simulator and natural overland flow also indicate that analogous processes control PP detachment and entrainment. Furthermore, the same DRP and PP transport processes appear to be operating across plot scales; NPRP and WEPP simulators used 2- and 32.6-m^2 plots while cited watershed studies ranged from 2 to 6 ha.

Because of the effects of flow-path length and landscape hydrology on overland flow and P transport, this study shows that inferences from simulated rainfall-runoff experiments on small plots should be limited to quantifying relationships between overland flow DRP and soil P and in assessing sediment discharged, PP, and P enrichment. This is the case for grassed and no-till situations where plant and residue cover protects the surface soil from flow interaction, as well as for tilled situations.

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