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Amounts and Forms of Dissolved Phosphorus Lost with Surface Runoff as Affected by Phosphorus Management and Soil Conservation Practices

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SUMMARY OF BACKGROUND AND OBJECTIVES

Excess phosphorus (P) delivery to water bodies via surface runoff results in excess algae growth that impairs water quality to undesirable and even harmful levels. Usually measured runoff P fractions in research are dissolved reactive P (DRP) and total P, which includes DRP, other dissolved P forms, and particulate P. With tillage and large soil loss, the majority of the P lost is particulate P and major efforts in Iowa focus on reducing soil erosion and surface runoff. For this reason, the Iowa Nutrient Reduction Strategy (INRS, 2013) estimates of P loss reduction by management practices by emphasizing total P loss, although it was recognized that the dissolved P component warrants further study and consideration. The Iowa P Index considers both DRP and total P, however (NRCS, 2004). Recent research in the Lake Erie watershed and in Iowa has suggested that the amount of dissolved P loss and its impact on water quality is greater than often assumed. Iowa research showed higher dissolved P loss with fertilizer than with manure and that some conservation practices that reduce erosion and particulate P loss with runoff, such as no-till, may increase dissolved P loss (Laflen and Tabatabai, 1984; Allen and Mallarino, 2008; Kaiser et al., 2009; Mallarino et al., 2013; Mallarino and Haq, 2015, Mallarino and Haq, 2016).

The DRP analysis, which has been used in the majority of runoff studies and surveys, measures dissolved orthophosphate (PO_4^{-3}) by a colorimetric procedure (Murphy and Riley, 1962) after filtering runoff through a 0.45 um filter. Few studies have measured total dissolved P (TDP) in surface runoff. The TDP measures all the dissolved P forms passing through a 0.45 um filter by digesting the filtrate by various possible methods to change all P forms to orthophosphate and measurement P by the Murphy and Riley method or inductively coupled plasma (ICP) methods. The ICP determination has also been used to measure P in filtered or centrifuged soil extracts, and test results are higher than for the Murphy and Riley method because the very hot flame vaporizes and ionizes all P forms in the solutions (Rowland and Haygarth, 1997; Mallarino, 2003). The non-orthophosphate dissolved P in filtered extracts has been shown to be mainly dissolved organic P forms (Mallarino and Borges, unpublished, Iowa State University) but sometimes also colloidal-sized inorganic or organic P forms (Rowland and Haygarth, 1997) all of which quickly decompose or hydrolyze to forms immediately available to algae. Analysis of both DRP and TDP in few samples from two Iowa surface runoff studies showed that DRP can range from 15 to 100% of the TDP with a 66% average (Mallarino and Helmers, unpublished).

Therefore, better knowledge of amounts and forms of dissolved P in runoff for a range of management practices is critical to improve the understanding and prediction of runoff P loss impacts on water quality. This type of data is needed for better consideration of dissolved P by the Nutrient Reduction Strategy.

Specific objectives of the project were

1. Determine the amount of runoff dissolved P not measured by the commonly used DRP method that erroneously is being considered particulate P for a variety of management practices and conditions
2. Study how the amounts of DRP and TDP in runoff can be estimated by routine soil-test P methods recommended for crops that are included in the Iowa P Index, water-extractable soil P, and an index of soil P saturation.

SUMMARY OF PROCEDURES

The study used soil and surface runoff samples from several Iowa field experiments with corn or soybean with different soils and management systems. Eleven soil series were represented in the study, all with large areas in Iowa and predominant corn and soybean production. These were Canisteo, Clarion, Downs, Flagler, Galva, Mahaska, Nevin, Nicollet, Nira, Schley, and Sharpsburg with soil texture (15-cm depth) loam, clay loam, silt loam, or silty clay loam. Treatments varied across the several experiments and evaluated fertilizer or manure P application rates; tillage systems (no-till and chisel-plow/disk); soil amendments alum ($Al_2(SO_4)_3$) or gypsum ($CaSO_4$), and the conservation practices cover crops or prairie filter strips. Multi-year experiments were conducted in one site for three to four years and single-year experiments were conducted at two to twelve different sites in one or two different years. Treatments of all experiments were replicated three to four times, and all replications were used for this study.

The trials included wide ranges of initial soil-test P (STP) levels and 1,181 composites soil samples were collected and analyzed. Composite soil samples were collected from each research watershed or plot for analysis prior to applying fertilizer, manure, or soil amendments and before any runoff occurred. Soil samples were taken from depths of 0-5 and 5-15 cm, but only results for the top 5-cm depth were used in this study because previous research has shown that with no-till management this sampling depth often relates better with P loss with surface runoff than sample samples taken from the top 15-cm depth recommended for crop production. The samples were oven-dried at 35-40° C and crushed to pass through a 2-mm sieve.

Soil was analyzed for Bray-1 P, Mehlich-3 P, and Olsen P following procedures recommended by the North Central Regional Committee for Soil Testing and Plant Analysis (NCERA-13) for the North Central Region (NCERA-13, 2015). Soil was also tested for water-extractable P (WEP) with the procedure describe by Pote et al. (1996), for which 1 g of soil was extracted with 25 mL of deionized water by shaking for 1 hour and both centrifuging and filtering through Whatman no. 42 filter paper. Phosphorus in all extracts was determined colorimetrically with the ammonium-molybdate ascorbic-acid method (Murphy and Riley, 1962). Soil extractable Al, Ca, and Fe were measured using the Mehlich-3 extractant and were determined by inductively-couple plasma (ICP). Degree of soil P saturation (DPS) was estimated with the Mehlich-3 extractant and was calculated using molar-ratios in two different ways, $[P_{M3}/(Ca_{M3}) \times 100]$ and $[(P_{M3}/(Al_{M3}+Fe_{M3})) \times 100]$, which will be referred to as $M3DPS_{Ca}$ and $M3DPS_{AlFe}$, respectively (Khiari et al., 2000; Maguire and Sims, 2002; Kleinman et al., 2002). Soil pH was measured using a 1:1 soil:water ratio as recommended by the NCERA-13 committee. Soil organic matter was determined by a combustion method (Wang and Anderson, 1998).

The several runoff experiments from which soil and runoff samples were collected were conducted under natural rainfall (in small watersheds or large plots) or by using simulated rainfall in small field plots. The field experiments under natural rainfall evaluating prairie filter strips were led by Dr. Mathew Helmers (Department of Agricultural and Biosystems Engineering) and those evaluating tillage systems and cover crops or P sources (fertilizer or manure) were led by co-investigators Drs. Antonio Mallarino and Matthew Helmers. The watershed field-scale studies used H-flumes and automatic runoff monitoring and sampling equipment. The studies in large plots under natural rainfall used a tipping-bucket runoff monitoring and sampling system. All field rainfall simulation experiments evaluating effects of fertilizer or manure P application rates and other soil amendments were led by Dr. Mallarino. For the field rainfall simulations experiments, a portable rainfall simulator was built based on a design by Miller (1987) with minor structural modifications suggested by the SERA-17 National Phosphorus Research Project (SERA-17, 2002).

A total of 1,244 surface runoff samples were utilized, which were collected from ongoing field experiments or had been appropriately stored from completed field experiments. Unfiltered runoff samples were analyzed for total P and bioavailable P (BAP). Total P was determined with the alkaline-oxidation digestion procedure utilizing a sodium hypobromite solution (Dick and Tabatabai, 1977).

Bioavailable P was analyzed with the iron-oxide impregnated filter paper method described by Sharpley (1993). Phosphorus in the total P digests and BAP extracts was measured colorimetrically with the ammonium-molybdate ascorbic-acid method (Murphy and Riley, 1962). Runoff samples were filtered through 0.45-um filters and the solution was analyzed for dissolved reactive P (DRP) by the Murphy and Riley method and also for total dissolved P (TDP) by directly using ICP (Rowland and Haygarth, 1997). A small subset of filtered samples was digested using the aforementioned sodium hypobromite method and the P in the digests was measured colorimetrically by the Murphy and Riley method to compare results with the direct TDP measurement by ICP. Particulate P was calculated as the difference between TP and either DRP or TDP as is commonly done in surface runoff research. For some experiments, BAP data were not available because unfiltered runoff samples had been analyzed by total P, filtered for dissolved P, and only the filtered samples were stored.

Simple correlation and linear regression analyses were used to study relationships among the runoff P fractions (DRP, TDP, BAP, and total P) and between each soil P measurement and each runoff P fraction, because the quadratic polynomial term or other curvilinear models were not significant compared with the linear models. To assess effects of the different management practices on the runoff P fractions and runoff volume, analyses of variance were performed for effects of P rate (0 to 50 kg P ha^{-1}), P source (fertilizer, manure, or none), tillage systems (no-till and chisel-plow/disk tillage), crop (corn or soybean), soil amendments alum or gypsum, cover crops (with or without winter cereal rye), and filter strips (with or without). Analysis of variance assessed as appropriate for the different experiments and treatments effects (main effects and interactions when applicable) were performed with the GLIMMIX procedure of the SAS statistical package. A few of the experiments had more than two levels of the main factors eveluated, and in this case differences between the treatment means were assessed with the LINES option of the LSMEANS statement of GLIMMIX only when the treatment main effects or interactions were significant at $P \leq 0.05$.

RESULTS AND DISCUSSION

Soil Properties and Relationships Among Soil-Test P Methods

Table 1 shows the wide range of several soil chemical properties observed across soil samples taken across all sites, treatments, and replications from a 5-cm depth. Soil-test P for the Bray-1, Mehlich-3, Olsen, and WEP tests ranged from 2 to 442, 4 to 573, 3 to 159, and 0.05 to 84 ppm, respectively. Matching results for a 6-inc sampling depth for the three routine soil tests Bray-1, Mehlich-3, and Olsen were 2 to 278, 3 to 480, and 2 to 141 ppm, which ranged from very deficient to several times higher than values deemed optimum for crops. Water-extractable P ranged from almost zero to 84 ppm but the vast majority of samples tested very low (median 5 ppm) which is commonly the case except when P was applied recently. Degree of soil P saturation estimated by $M3DPS_{Ca}$ ranged from 0.5 to 19% and for $M3DPS_{AlFe}$ ranged from 0.5 to 48%. Much higher soil DPS have been observed in eastern states with much higher STP levels.

There were strong linear relationships among STP extracted (r^2 0.80 to 0.98; $P \leq 0.01$) by the three routine P tests, Bray-1, Mehlich-3, and Olsen (not shown). Relationships involving Olsen were weaker, which has been showed before in Iowa by Mallarino (1997) and Mallarino and Atia (2005) among others. The relationships between WEP and the routine Bray-1, Mehlich-3, and Olsen tests were also linear with r^2 values of 0.78, 0.78, and 0.69 ($P \leq 0.01$), respectively (not shown). The poorer but still strong relationship between each routine soil P test and WEP may seem surprising but this is the reason WEP is not used nor recommended for crop production because it estimates crop-available P very poorly. The reason for the observed correlation is because of the very wide range of soil-test values included in the experiments, often with values much higher than the range relevant for crops but commonly observed in fields with long histories of manure application. Both DPS measurements were linearly and highly correlated with STP (not shown).

Table 1. Selected soil chemical properties across all samples (5-cm depth).

Soil Property	Minimum	Maximum	Median
Bray-1 P, ppm	2	442	40
Mehlich-3 P, ppm	4	573	39
Olsen P, ppm	3	159	22
Water-extractable P, ppm	0.1	84	5
Mehlich-3 Ca, ppm	1,357	14,815	2,400
Mehlich-3 Al, ppm	81	1,380	689
Mehlich-3 Fe, ppm	64	1,011	183
Mehlich-3 $DPS_{(Ca)}$, %†	0	18	1.8
Mehlich-3 $DPS_{(Al+Fe)}$, %‡	0.5	43.8	5.1
pH	4.58	8.13	6.2
Organic matter, %	2.15	7.49	4.36

† $DPS_{(Ca)}$, degree of P saturation calculated by (P_{M3}/Ca_{M3}) x 100.
‡ $DPS_{(Al + Fe)}$, degree of P saturation by $[P_{M3}/(Al_{M3} + Fe_{M3})]$ x 100

Measurement of Runoff Total Dissolved P

Although many studies have proved that in soil P extracts measuring dissolved reactive P (DRP) by the Murphy and Riley method on samples filtered through 0.45-um filters underestimates total dissolved P (TDP), few studies have compared these two methods for surface runoff. Since an important objective of this study was to assess runoff dissolved P that is not measured by DRP on many runoff samples we chose to do it using the direct ICP measurement after filter runoff. We felt necessary, however, to demonstrate that the ICP and digestion methods provide approximately similar results. Therefore, a small subset of filtered samples was digested using the aforementioned sodium hypobromite method and the P in the digests was measured colorimetrically by the Murphy and Riley method to compare results with the direct TDP measurement by ICP. Results in Fig. 1 demonstrates that indeed, runoff TDP measured directly by ICP is equivalent to the total P measurement after digesting the filtered samples.

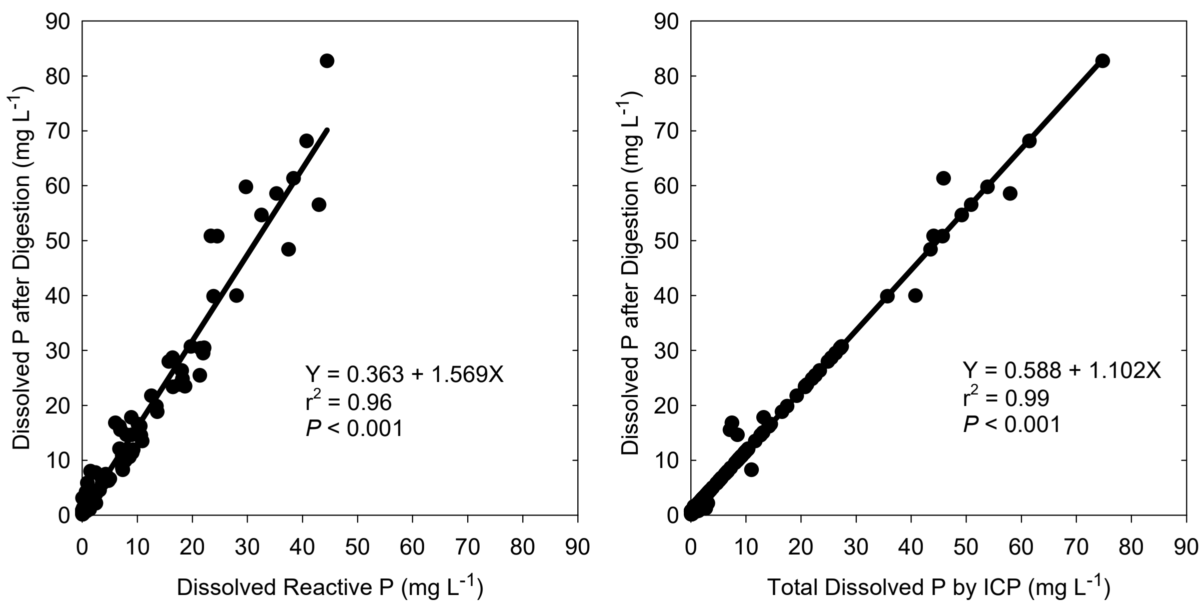

Figure 1. Relationship between dissolved runoff P concentration measured after digesting filtered samples and concentrations of dissolved-reactive P or total dissolved P without digesting extracts (means across replications).

The graph showing the relationship between TDP after digestion and DRP demonstrates how DRP underestimates dissolved P. However, the graph showing the relationship between TDP by digestion and TDP by ICP demonstrate that results are essentially identical. Our results are of practical importance because the ICP measurement is much easier and less costly than a digestion followed by P measurement.

Surface Runoff P and Relationships Among Fractions

Table 2 shows observed ranges of runoff concentrations of several measurements across all samples collected from each runoff event. There were wide ranges observed for all runoff measurements. Calculations from DRP and TDP means across all 1,242 runoff samples (0.48 and 0.62 mg L^{-1}, respectively) indicate that DRP did not measure 14% of TDP (1.79 and 2.19 mg L^{-1}, respectively). There were more samples for DRP and TDP than for BAP or total P because for some experiments data could not be obtained or samples were not analyzed. Therefore, results for BAP, total P and particulate P calculated by subtracting either DRP, TDP, or BAP cannot be directly compared with DRP and TDP.

Table 2. Summary statistics of runoff concentration measurements by event across all samples.

Measurement	Minimum	Maximum	Median	Mean	Samples†
	------------ Concentrations (mg L^{-1}) ------------				
Dissolved-reactive P (DRP)	0.01	45.0	0.48	1.79	1,242
Total dissolved-P (TDP)	0.01	52.7	0.62	2.19	1,242
Bioavailable P (BAP)	0.04	52.7	1.52	3.66	510
Total P	0.13	61.7	2.08	4.55	728
Particulate P from Total P - DRP	-0.30	25.7	0.96	1.77	728
Particulate P from Total P - TDP	-4.58	28.4	0.60	1.19	728
Particulate P from Total P - BAP	-2.07	17.6	0.80	1.44	510
Total solids (TS)	0.01	16,850	570	958	607

† There were fewer samples for total P and even fewer for BAP and TS because for some experiments data could not be obtained or samples could not be analyzed.

Table 3 shows runoff concentration descriptive statistics for a smaller set of runoff samples for which all runoff fractions were measured and, therefore, are directly comparable. Calculations from DRP, TDP, and total P means (3.10, 3.67, and 5.09 mg L^{-1}, respectively) indicate that on average DRP did not measure 16% of TDP and total runoff P comprised by DRP and TDP was 61 and 72%, respectively. The statistics for TDP and BAP concentrations were almost exactly the same, so the BAP measurement did not measure any additional dissolved, dissolvable, or hydrolysable runoff P that TDP did not measure.

Table 3. Summary runoff concentration statistics for a partial set of samples for which all runoff P fractions were measured.

Measurement	Minimum	Maximum	Median	Mean	Samples
	------ P Concentrations (mg L^{-1}) ------				
Dissolved-reactive P (DRP)	0.02	45.0	1.18	3.10	510
Total dissolved-P (TDP)	0.05	52.7	1.53	3.67	510
Bioavailable P (BAP)	0.04	52.7	1.52	3.66	510
Total P	0.13	61.7	2.63	5.09	510
Particulate P from Total P - DRP	-0.29	25.9	1.17	2.00	510
Particulate P from Total P - TDP	-4.33	28.4	0.76	1.42	510
Particulate P from Total P - BAP	-2.07	17.6	0.80	1.44	510

Therefore, an important result of the study is that DRP underestimated dissolved P in runoff and makes the particulate P portion larger than should be. Since the BAP measurement is much more labor intensive than the TDP measurement, results suggest that measuring DRP underestimates the short-term impact of runoff P on water quality, and the simple TDP measurement accounts for BAP. Previous research with soil or drainage extracts has shown that the additional dissolved P measured by ICP compared with the Murphy and Riley method include mainly simple organic P forms (Rowland and Haygarth, 1997; Mallarino and Borges, unpublished, Iowa State University).

Figure 2 shows that relationships among the concentrations of runoff P fractions across all samples were linear and were the strongest among DRP, TDP, and BAP (r^2 0.95 to 0.98). This result is reasonable because these P fractions consist of dissolved or easily dissolvable P forms. The relationships between particulate P (calculated by subtracting DRP or TDP from total P) and DRP, TDP, or BAP were weaker (r^2 0.39 to 0. 57). The relative concentration of DRP and TDP fractions calculated as their ratio was not correlated with total runoff P (not shown). Relationships between runoff total P and DRP, TDP or BAP (not shown) also were strong (r^2 0.92 to 0.95, respectively) because the dissolved P fraction often was a major proportion of the total P.

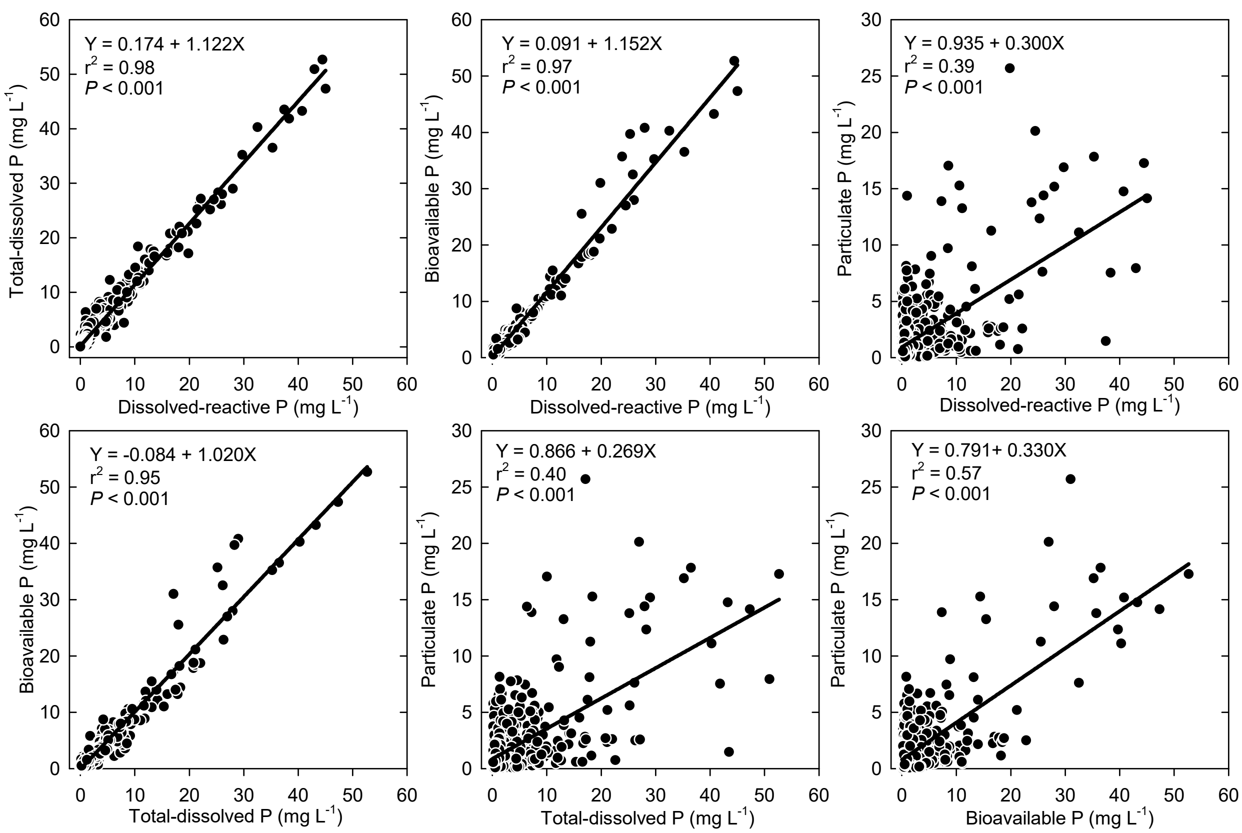

Figure 2. Relationships among concentrations of several runoff fractions across all runoff samples.

Relationships between Soil-Test P and Surface Runoff P Fractions

Figure 3 shows relationships between STP measured by four methods and concentrations of DRP or TDP in runoff for soils not fertilized since the last soil sampling. Extensive previous research in Iowa and other states has shown that applied P since a soil sampling precludes otherwise good relationships between STP and the loss of all runoff P fractions. The relationships for DRP were linear with approximately similar strength for the three routine STP methods (r^2 0.42 or 0.45), but the relationships between the STP methods and WEP was stronger (r^2 0.56). Relationships for TDP also were linear but poorer than for DRP for all four STP methods. As for DRP, relationships between STP and TDP were poorer for the routine tests (r^2 24 or 25) than for WEP (r^2 0.36).

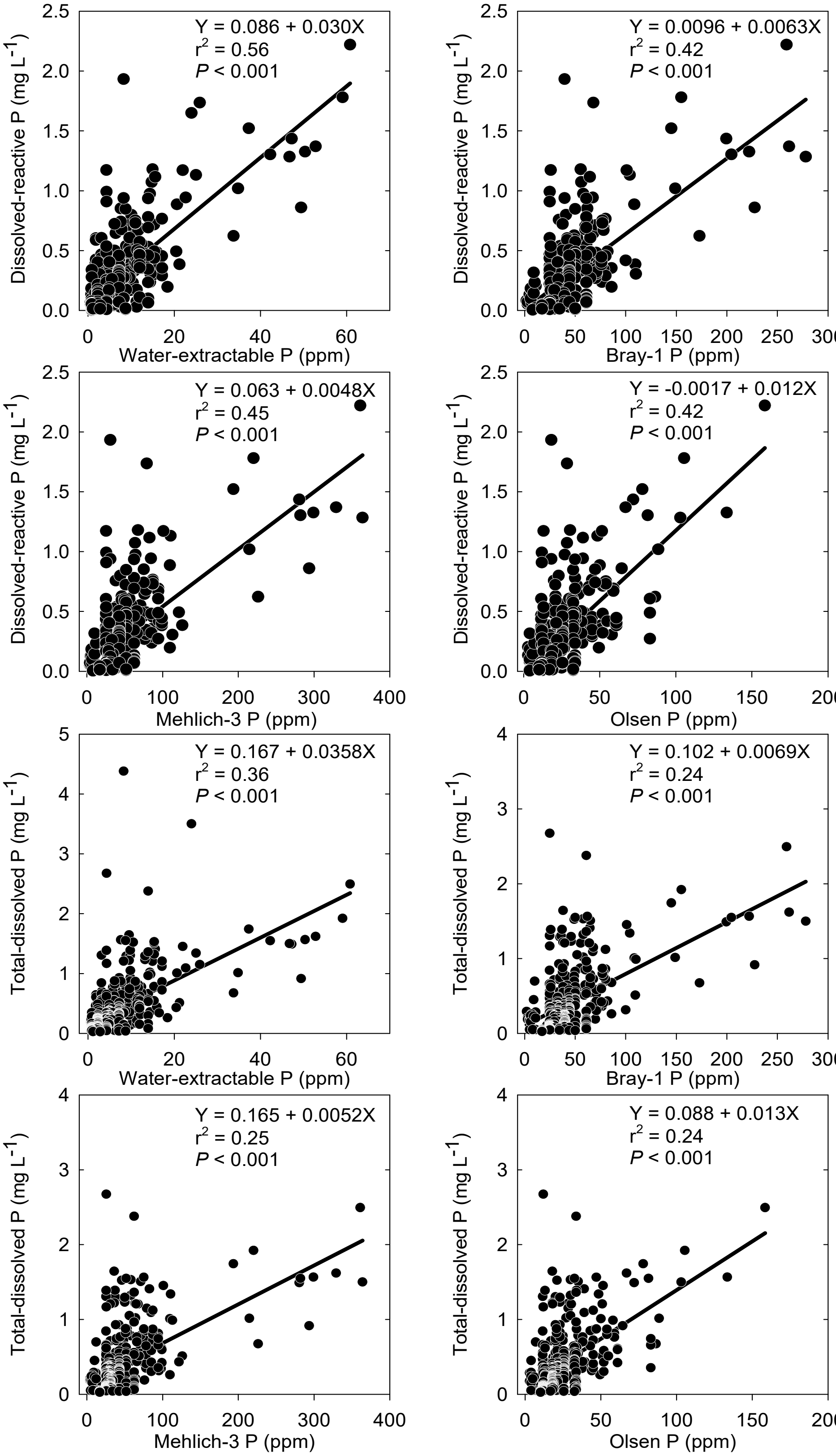

Figure 3. Relationships between soil-test P by four methods and runoff dissolved reactive P or total dissolved P for soils receiving no P since soil sampling (means across replications).

Figure 4 shows that relationships between STP and runoff BAP or total P concentrations also were linear. The strength of relationships for BAP (r^2 0.42 to 0.47) were approximately similar to those for DRP, but relationships for total P were much poorer (r^2 0.01 to 0.10), which agrees with expectations.

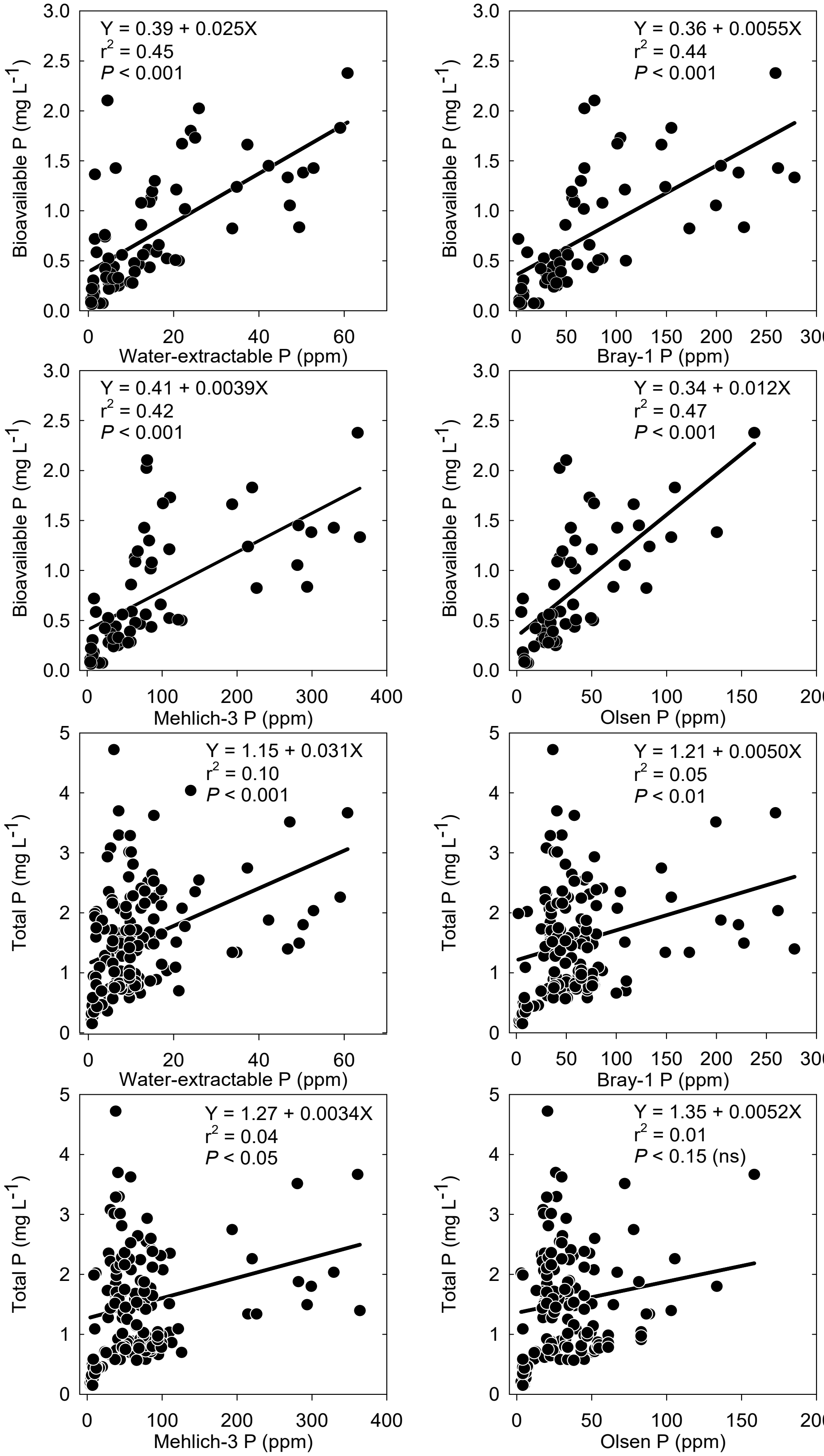

Figure 4. Relationships between soil-test P by four methods and runoff bioavailable P or total P for soils receiving no P since soil sampling (means across replications).

Reasons for slightly better relationships between DRP and STP than for TDP and STP (Fig. 3) are not very obvious. A reason might be that the additional dissolved P forms other than orthophosphate by TDP do not have a match with STP since measured soil extracted P was only orthophosphate by the Murphy and Riley method.

The runoff DRP and TDP concentrations increased with increasing soil P saturation, although as expected there was very high variability given Iowa soil properties and not extremely high STP levels. Figure 5 shows relationships between runoff DRP concentration and the two measurements of degree of soil P saturation (DPS) and also relationships between the runoff DRP/total P concentration ratio and both DPS measurements. Relationships for TDP are not shown because were similar (the DPS did not affect the DRP/TDP ratio). The strength of the relationships between DRP concentration and either DPS measurement was stronger (r^2 0.43 for both DPS measurements) than relationships for the DRP/total P ratio (r^2 0.17 for both DPS measurements). It is noteworthy that the r^2 for DRP concentrations in Fig. 5 are similar to r^2 for relationships between DRP concentration and STP by the routine tests (Fig. 3). This is the reason DPS was not included in the Iowa P Index. In some eastern states having soils with weaker P retention and much higher STP and DPS levels (often with STP higher than 1000 mg P kg^{-1} and DPS up to 90%), sometimes the DPS relates better with runoff DRP than the routine soil P tests.

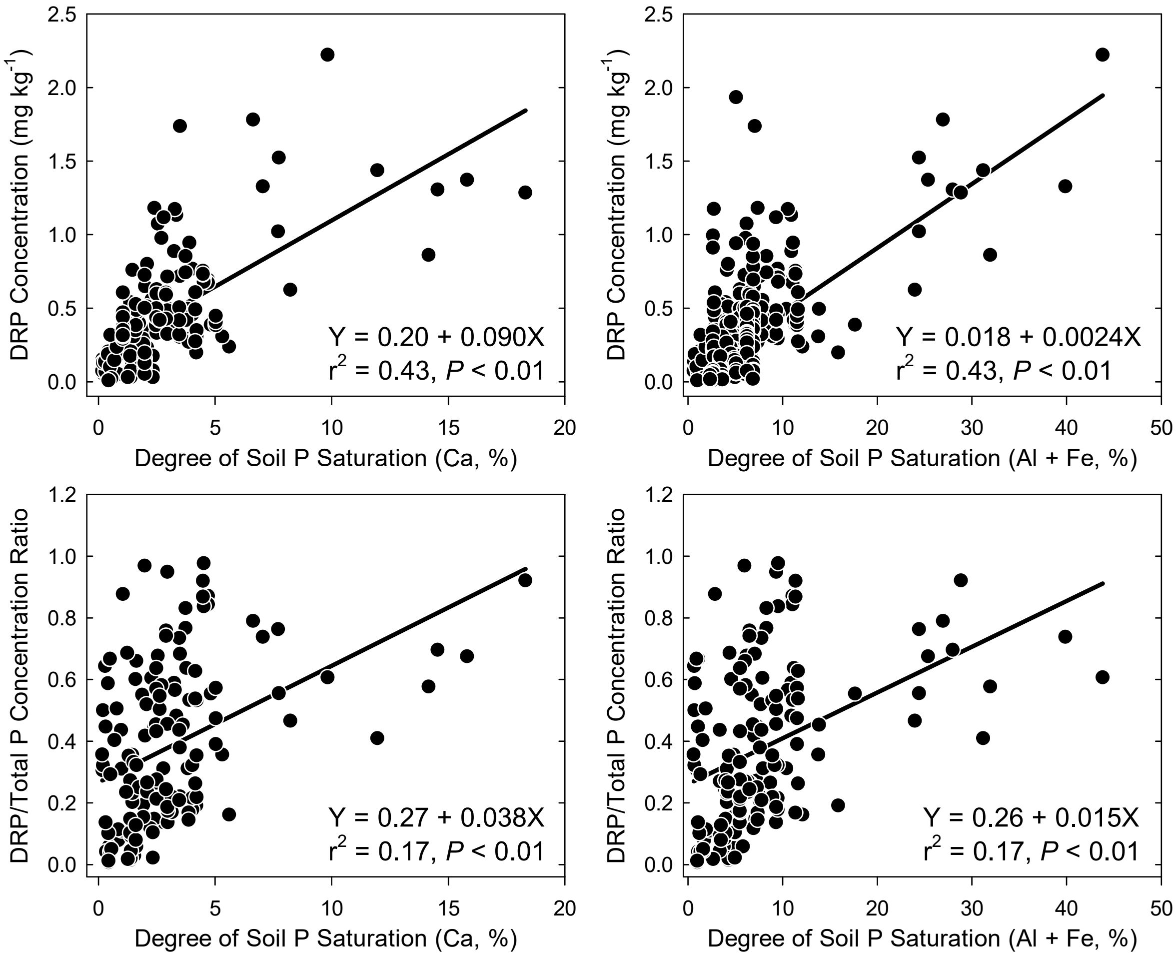

Figure 5. Relationships between runoff dissolved reactive P concentration (DRP) or the DRP/total P concentration ration and two estimates of soil degree of P saturation (means across replications).

Relationships between STP or DPS and runoff P loss are not shown because all relationships were linear and rankings concerning strength of the relationships was similar to those for concentrations, although there was much more variability (r^2 were 0.11 or lower). Higher variability in relationships for runoff P losses than for runoff P concentrations is almost always observed many in field trials due to high variability in runoff volume.

Figure 6 shows, relationships for the total P/DRP concentrations ratio and the particulate P/DRP concentrations ratio with STP by either WEP or the Bray-1 routine method. The graphs for the Bray-1 method show that particulate P was many times higher than DRP from very low STP values (close to zero) until approximately 50 ppm (and essentially equal to total P), was about ten times higher than DRP between about 50 and 80 ppm, and became approximately constant at about twice or less for higher STP values. The graph for WEP show similar trends, but for the typically lower WEP values. Proportionally similar trends were observed for the Mehlich-3 and Olsen routine STP methods (not shown). These results are reasonable because Iowa soils have a little capacity to transform added P into unavailable or highly retained (fixed) P forms and very high STP values result in increased dissolved P loss relative to particulate P loss.

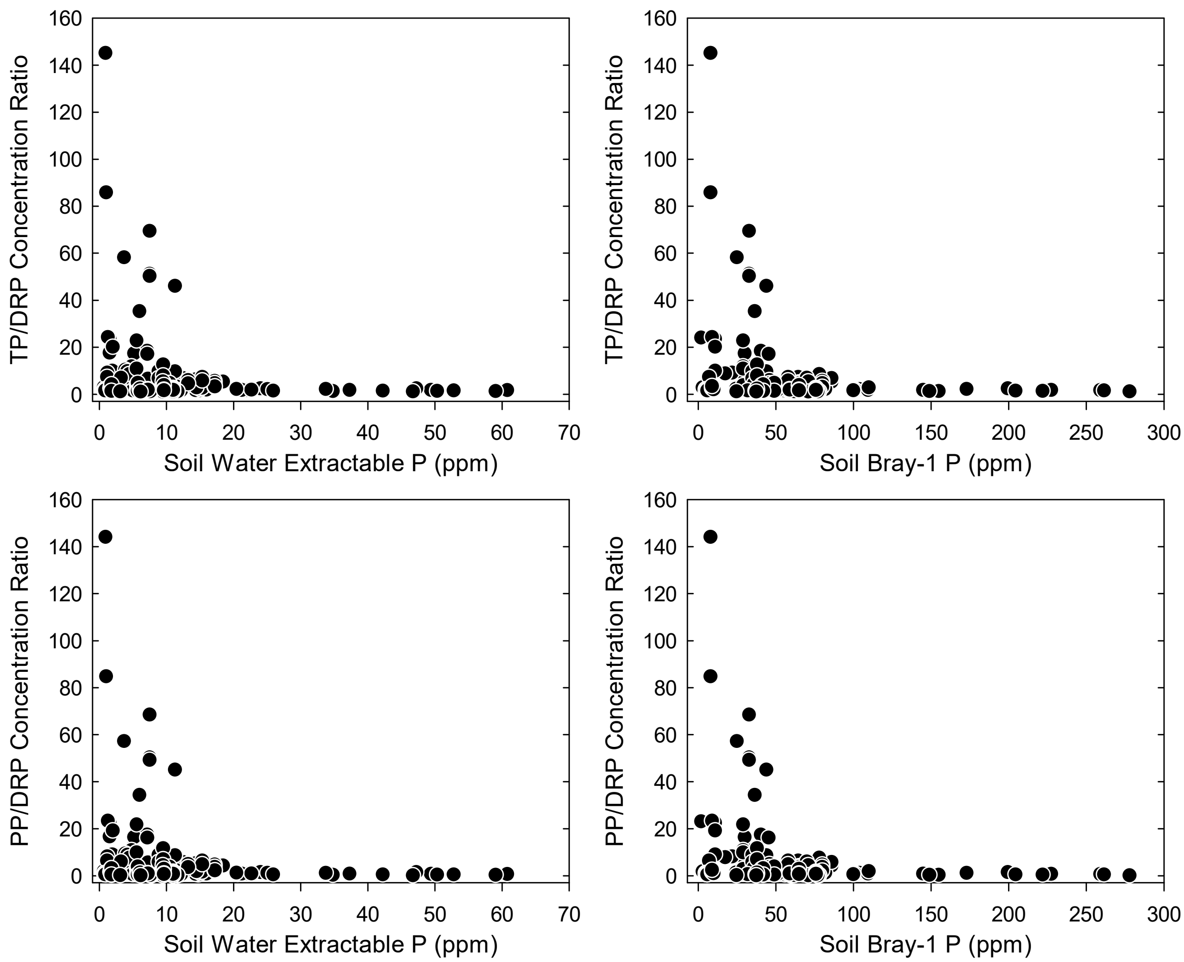

Figure 6. Relationships between the ratio of total P (TP) or particulate P (PP) to dissolved reactive P (DRP) and water-extractable soil P or Bray-1 soil-test P for soils that received no P fertilizer or manure since the soil sampling (means across replications).

Management Effects on Runoff Dissolved P Fractions

Phosphorus P application rate.

Table 4 shows effects of the P application rate for corn and soybean across P sources and placement methods on runoff DRP, TDP, and total P concentrations and losses, all of which were statistically significant. The P rate did not affect BAP concentrations but did affect BAP losses. The P rate did not affect runoff flow (not shown). Results for BAP concentrations and losses are not shown in Table 5 because fewer samples were analyzed for BAP and results cannot be directly compared to those for the other fractions.

There was a very large effect of the highest P rate applied (50 kg P ha^{-1}) and a much lower effect of the 25-kg rate on runoff P concentrations and losses. The 25-kg rate is approximately the annual P rate needed to maintain optimum STP for corn and soybean. The 50-kg often is applied only once before corn to maintain optimum STP for the rotation and also when applying N-based manure for corn even in high-testing soils. The DRP/TDP ratio was not correlated with the P rate for runoff concentrations or losses, but the DRP and TDP proportions of the total runoff P increased exponentially as the P rate increased (not shown).

Table 4. Effect of the P application rate on the concentrations and losses of several runoff P fractions (means across experiments, sites, and replications).

	P Application Rate (kg P ha^{-1})					
Runoff P Fraction†	0	25	50	0	25	50
	-- P Concentrations (mg kg^{-1}) --			------- P Losses (g ha^{-1}) -------		
Dissolved reactive P (DRP)	0.58‡b	0.67b	3.98a	66b	84b	585a
Total dissolved P (TDP)	0.78b	0.84b	4.70a	85b	116b	688a
Total P (TP)	1.64b	2.06b	6.17a	156b	293	927a
Particulate P by TP-DRP	1.07b	1.39b	2.19a	90c	209b	342a
Particulate P by TP-TDP	0.87b	1.22b	1.46a	71c	178b	239a

† Bioavailable P is not shown because was not measured in some sites and P effects were not significant.
‡ Different letters within each row for concentrations or losses indicate significant differences at $P \leq 0.05$.

Tillage system and crop interactions.

Data used for this section are from three multiyear field experiments at three sites and three single-year trials at three different sites and years that evaluated effects of two tillage systems (no-till and chisel-plow/disk or disk tillage) on surface runoff P in corn-soybean rotations among other treatments. Any other treatment evaluated at each experiment were similar for each tillage system and crop. To achieve the objectives of this study we analyzed for TDP stored runoff samples that had been filtered through 0.45 um filters from recently completed field studies and used results for runoff DRP, BAP, and total P from previously conducted analyses. The results are shown across all studies, years, and replications.

Table 5 shows the effects of tillage systems (chisel-plow/disk or no-till) and crops (corn or soybean) on runoff P concentrations and losses for DRP, TDP, BAP, and total P. Fewer samples were analyzed for the BAP fraction than for the others, so results cannot be directly compared to the other fractions. Runoff P concentrations of all fractions were much higher in the corn year (planted on soybean residue) than in the soybean year (planted on corn residue) with both tillage systems, with larger proportional differences with no-till. The tillage system affected runoff P concentrations in an inconsistent way for the different P fractions and crops (there were significant tillage by crop interactions). The DRP, TDP, and BAP concentrations were not affected by tillage in the soybean year but were higher with no-till in the corn year. The total runoff P concentrations, however, were higher with tillage in the soybean year but higher with no-till in the corn year.

Runoff P concentration differences can be misleading and may have less relevance in situations when treatments affect water loss with runoff. There were statistically significant main effects of tillage system and crop on runoff flow, but the crop effect was very small and there was no significant interaction (not shown). On average across years, runoff in the corn year (planted on soybean residue) was 12.7 and 14.6 mm with tillage and no-till, respectively, and in the soybean year (planted on corn residue) was 13.1 and

15.4 mm with tillage and no-till, respectively. Therefore, runoff flow was slightly more with no-till for both crops.

Table 5. Runoff dissolved reactive P and total dissolved P fractions concentrations and losses as affected by tillage and crop of corn-soybean rotations across all sites.

Tillage	P Concentrations (mg L^{-1})			P Losses (g ha^{-1})		
treatment	Soybean	Corn	Means	Soybean	Corn	Means
--- Dissolved-reactive P ---						
Tillage	0.98a†	1.41b	1.20b*	99b	214b	157b*
No-till	0.98a	2.01a	1.49a*	298a	318a	308a*
--- Total Dissolved P ---						
Tillage	1.27a	1.78b	1.53b*	130b	267b	199b*
No-till	1.21a	2.55a	1.88a*	353a	391a	372a*
--- Bioavailable P‡ ---						
Tillage	1.70a	2.22b	1.96a*	230b	403b	317b*
No-till	1.53a	2.59a	2.06a*	501a	426a	464a
--- Total P ---						
Tillage	2.28a	3.00b	2.64a*	261b	484a	373b*
No-till	1.71b	3.31a	2.51a*	402a	510a	456a*

* Significant difference between crops for each measurement at $P \leq 0.05$.
† Numbers with different letters for each column and measurement differ at $P \leq 0.05$.
‡ Bioavailable P data cannot be compared with other fractions due to fewer analyzed samples.

Results for the runoff P loss also shown in Table 5 show that the loss of most runoff P fractions was greater with no-till than with tillage, the only exception being for total P in the corn year (planted on soybean residue) did not attain statistical significance at $P \leq 0.05$. Proportionally, the differences for all runoff fractions were greater in the soybean year (planted on corn residue) than in the corn year, especially for DRP and TDP losses. The table also shows that the loss of most runoff P fractions was greater in the corn year than in the soybean year (planted on corn residue) with tillage with the only exception of BAP loss with no-till. Proportionally, the differences for all runoff fractions except BAP were greater with tillage than with no-till. The different results for the BAP fraction are difficult to explain and might be explained by the fewer number of observations since was not measured in some experiments. Calculations from data in Table 5 indicate that the underestimation of dissolved P loss by DRP (compared with TDP) was slightly affected by the tillage system only in the soybean year (planted on corn residue), being 24% with tillage and 16% with no-till.

In a previous 6-year study (Mallarino et al., 2013) there was no overall tillage or crop effects on runoff flow because runoff and the timing of most flow varied greatly over the years as affected by the amount and timing of the largest runoff events and this was also the case in experiments included for our study. Some may expect always more runoff with tillage than with no-till, but the temporal variation and on average more runoff we found for no-till is a common result, which has been attributed to more soil compaction with no-till (mainly due to wheel traffic) and variable residue cover between systems mainly when moldboard plowing is not used for the tillage (Voorhees and Lindstrom, 1983; Lindstrom and Onstad, 1984; Benoit and Lindstrom, 1987). That study (Mallarino et al., 2013) showed that on average across the 6 years there were greater runoff DRP, BAP, and total P losses with tillage than with no-till and greater losses in the corn year than in the soybean year. These results were explained by greater soil loss with tillage and in the corn year (planted on soybean residue) and by applying the two-year P rate for the rotation only before corn, since runoff flow was very variable within and across years and was not affected by the treatments. In our study, however, which included data from several experiments, on average there was slightly more runoff flow with no-till than with tillage and slightly more in the soybean year than in the corn year and, most importantly, the P was applied either before corn or soybean.

Table 6 shows that the crop did not affect significantly ($P \leq 0.05$) the proportion of the total P loss comprised by DRP, TDP, and BAP. However, the proportions of these three runoff fractions of total P were consistently much higher with no-till than with tillage for both crops. With no-till, on average across crops, the proportions of DRP, BAP, and TDP loss of the total P loss was 68, 82, and 75%, respectively, whereas with tillage the proportions were 41, 52, and 53%, respectively.

Table 6. Proportion the total runoff P loss comprised by two dissolved P fractions and bioavailable P as affected by tillage and crop in corn-soybean rotations.

Tillage	Dissolved-reactive P			Total-dissolved P			Bioavailable P†		
treatment	Soybean	Corn	Mean	Soybean	Corn	Mean	Soybean	Corn	Mean
	------------------------------- Percent of Total Runoff P Loss ---------------------------								
Tillage	38‡b	44b	41b	50b	55b	53b	51b	54b	52b
No-till	74a	62a	68a	88a	77a	82a	77a	73a	75a

† Bioavailable P data cannot be compared with other fractions due to fewer analyzed samples.
‡ Numbers with different letters for each column differ at $P \leq 0.05$.

The results for tillage system effects on the proportion of DRP loss of the total P confirm findings of previous research for DRP (Laflen and Tabatabai, 1984; Allen and Mallarino, 2008; Kaiser et al., 2009; Mallarino et al., 2013), and our results for TDP and BAP showed similar trends. These results are important because these runoff P fractions are more rapidly available in surface water bodies than particulate P and are responsible for rapid algae growth and eutrophication.

Fertilizer and manure P sources.

Data used for this section are from two multiyear field experiments at two sites, three single-year similar experiments conducted at three different sites and years, and twelve similar experiments evaluated at different sites one year. These experiments evaluated effects of two tillage systems (no-till and chisel-plow/disk or disk tillage) and two or three of the P sources fertilizer, poultry manure, and liquid swine manure on surface runoff P in corn-soybean rotations. The P application rate was similar for all P sources at each study (0, 25, or 50 kg P ha^{-1}). To achieve the objectives of this study we analyzed for TDP stored runoff samples that had been filtered through 0.45 um filters from recently completed field studies and used results for runoff DRP, BAP, and total P from previously conducted analyses.

Table 7 shows that on average across all experiments, years, and replications the runoff P concentrations and losses of all fractions were higher with no-till than with tillage for the three P sources. These average tillage system differences agreed with tillage effects shown before in Table 5. On average across trials and years, runoff was slightly higher for no-till (17 mm) than with tillage (16 mm) and was not affected by the P source (not shown).

Table 7 also shows that the P application and P source effects on the runoff P concentrations and losses often differed across the tillage systems (there were significant interactions tillage by P source). With no P application, runoff DRP, TDP, and BAP concentrations and losses were higher with no-till than with tillage, but both total P concentrations and losses were higher with tillage. With no-till, DRP, TDP, and BAP concentrations and losses were higher for fertilizer than for the two manures (which did not differ probably because liquid swine manure was injected), and this was also found for total P concentrations but the total P loss was the lowest for solid poultry manure. With tillage, however, a remarkable result was much lower DRP, TDP, and BAP concentrations and losses for poultry manure than for fertilizer and swine manure (which did not differ) but although the total P concentration differed little among the sources, the loss was the lowest with solid poultry manure. Moreover, the DRP, TDP, and BAP losses for solid poultry manure were so low that statistically did not differ from the no P control. It is also noteworthy that the relative tillage differences for liquid swine manure were consistently smaller than for the other two P sources for all runoff P fractions. This result may be explained by injection of the liquid swine manure into the soil with both no-till and tillage systems.

Table 7. Runoff P concentrations and losses as affected by tillage and the P source across sites where these practices were compared.

	P Concentrations (mg L^{-1})			P Losses (g ha^{-1})		
P Source	Tillage	No-Till	Means	Tillage	No-Till	Means
---------- Dissolved-reactive P ----------						
Fertilizer	1.89a†	4.34a	3.12a*	309a	609a	459a*
Solid poultry manure	0.46b	2.09b	1.27c*	47b	236c	141c*
Liquid swine manure	2.08a	2.86b	2.47ab*	312a	515ab	413ab*
No P	0.14c	0.60c	0.37d*	12b	67c	39d*
---------- Total Dissolved P ----------						
Fertilizer	2.15ab	4.68a	3.41a*	359a	665a	512a*
Solid poultry manure	0.68c	2.55b	1.62c*	73c	295c	184b*
Liquid swine manure	2.46ab	3.32ab	2.89ab*	392a	588ab	490a*
No P	0.27cd	0.71c	0.49d*	23cd	84d	54c*
---------- Bioavailable P ----------						
Fertilizer	2.51a	4.97a	3.74a*	403a	700a	552a*
Solid poultry manure	0.84bc	2.63b	1.74c*	87b	312c	199c*
Liquid swine manure	2.45a	3.39ab	2.92ab*	351a	586b	468b*
No P	0.47c	0.80c	0.63d*	48bc	88d	68d*
---------- Total P ----------						
Fertilizer	3.96a	5.78a	4.87a*	685a	812a	749a*
Solid poultry manure	3.48ab	3.80c	3.64b*	330b	447b	389b*
Liquid swine manure	3.55ab	4.80b	4.18ab*	612ab	848a	730a*
No P	2.70c	1.61d	2.15c*	234bc	161c	197c*

* Significant difference between crops for each measurement at $P \leq 0.05$.
† Numbers with different letters for each column and measurement differ at $P \leq 0.05$.

Table 8 shows the proportion of the total P loss comprised by DRP, TDP, and BAP for effects of tillage and P source on runoff P losses shown in Table 7. Often there were tillage and P source differences and also significant interactions, which were explained mainly by different effects of solid poultry manure and liquid swine manure with tillage or no-till management. With tillage, solid poultry manure resulted by far in the smallest DRP, TDP, and BAP proportions of the total P loss (14, 22, and 26%, respectively), the DRP, TDP, and BAP proportions of the total P did not differ statistically for fertilizer and swine manure (on average 48% for DRP, 58% for TDP, and 58% for BAP). With no-till, however, the DRP, TDP, and BAP proportions of the total P loss were the highest for fertilizer (75% for DRP, 82% for TDP, and 86% for BAP) and did not differ for solid poultry manure and liquid swine manure (on average 57% for DRP, 68% for TDP, and 69% for BAP).

The finding that DRP, TDP, and BAP losses for solid poultry manure with tillage were so much lower than for fertilizer and liquid swine manure and statistically similar to losses from the no P control is very important since these are the runoff fractions P most active at causing eutrophication of surface water resources. These results may be explained by more effective removal of P by rainfall from solid poultry manure laying on the soil surface with no-till but not when incorporated into the soil. Although this result has been showed before by our research group for DRP and BAP (Kaiser et al., 2009; Mallarino and Haq, 2016), these are the first findings for TDP.

Table 8. Proportion total runoff P loss comprised by dissolved P and bioavailable P fractions as affected by tillage and the P source.

P Source	Tillage	No-Till	Means
--------------------------- Dissolved-reactive P (% of Total P) ---------------------			
Fertilizer	45a†	75a	60a*
Solid Poultry manure	14b	53b	33b*
Liquid Swine manure	51a	61b	56a*
No P applied	5b	42bc	23bc*
----------------------------- Total-dissolved P (% of Total P) ------------------------			
Fertilizer	52a	82a	67a*
Solid Poultry manure	22b	66b	44b*
Liquid Swine manure	64a	69b	67a*
No P applied	10b	52c	31bc*
-------------------------------- Bioavailable P (% of Total P) -------------------------			
Fertilizer	59a	86a	73a*
Solid Poultry manure	26c	70b	48b*
Liquid Swine manure	57a	69b	63ab*
No P applied	21c	54c	38bc*

* Significant difference between tillage systems for each measurement at $P \leq 0.05$.
† Numbers with different letters for each column and measurement differ at $P \leq 0.05$.

Calculations from runoff P loss data in Table 8 show that the underestimation of dissolved P loss by DRP (compared with TDP) was slightly higher with tillage than with no-till (on average across the three P sources was 23 and 14%, respectively). On average across tillage systems, the P source effect on the DRP underestimation of TDP was smaller for fertilizer and liquid swine manure (11 and 16%, respectively) than for poultry manure (28%). Given results of previous research with soil or drainage P extracts (Rowland and Haygarth, 1997; Mallarino and Borges, unpublished), we believe dissolved organic P forms explain proportionally higher TDP in runoff with tillage than with no-till and higher for poultry manure.

Alum and gypsum soil amendments mixed with poultry manure.

A study with field work conducted from 2009 through 2011 using a field rainfall simulation technique evaluated effects of finely ground alum or gypsum mixed with solid egg-layers poultry manure on runoff P loss at three different sites in three different years. Runoff TDP had not been measured, so to achieve our objectives we analyzed for TDP stored samples that had been filtered through 0.45 um filters and used results for runoff DRP, BAP, and total P from previously conducted analyses. The materials were applied to soybean residue in the fall with or without incorporation into the soil. Two other treatments were runoff events within 24 hours or ten days after the application and there were three replications. The manure P rate was 50 kg P ha^{-1}, and the mixed amounts of alum or gypsum were 946 and 798 kg ha^{-1}, respectively.

Table 9 shows average results across tillage and runoff events. There were statistically significant treatment effects with the only exception of runoff volume (not shown). Alum mixed with the poultry manure greatly reduced DRP, TDP, and BAP runoff concentrations and losses compared with the untreated manure to levels statistically comparable to the control receiving no P or alum, but did not affect total P for which apparent reductions are not significant at $P \leq 0.05$. On the other hand, gypsum mixed with the poultry manure did not affect runoff P. Apparent reductions were much smaller than with alum and did not reach statistical significance at $P \leq 0.05$. Previous research in southern and southeastern states also showed that alum mixed with litter from broilers feeding operations (manure mixed with some bedding) drastically reduced dissolved P loss with surface runoff.

Table 9. Effects of alum and gypsum applied with poultry manure on surface runoff P.

Treatment	Dissolved reactive P	Total dissolved P	Bioavailable P	Total P
------------ Runoff P Concentrations (mg L^{-1}) ------------				
No P, no alum	0.20b†	0.35b	0.42b	1.47b
Manure alone	1.10a	1.50a	1.47a	2.84a
Manure + alum	0.48b	0.78b	0.73b	2.09ab
Manure + gypsum	0.83a	1.35a	1.16a	2.33a
------------ Runoff P Losses (g ha^{-1}) ------------				
No P, no alum	30c	52c	62c	161b
Manure alone	155a	209a	204a	360a
Manure + alum	69bc	114bc	108bc	271ab
Manure + gypsum	94ba	178ab	145ab	261ab

† Numbers with different letters for each column and measurement differ at $P \leq 0.05$.

Calculations from Table 9 indicate that for untreated poultry manure the proportion of the total P loss comprised by DRP, TDP, and BAP was 43, 58, and 57%, respectively. The mixing of alum with manure drastically reduced the proportion of DRP, BAP, and TDP in runoff to 25, 42, and 40%, respectively. The mixing of gypsum slightly reduced the proportion of DRP (from 43% to 36%) but increased or did not affect the proportions of TDP and BAP. The DRP underestimation of dissolved P loss measured by TDP was much less for untreated manure (26%) than for alum-treated manure (40%) and gypsum-treated manure (56%), due to unclear reasons at this time.

Gypsum soil amendment with P fertilizer.

Field work for this study was conducted using a field rainfall simulation technique from fall 2016 through late spring 2017 and at another site from fall 2017 through late spring 2018. The chemical analyses of soil and surface runoff samples was finished in December 2018, but runoff TDP had not been measured because was not an objective. Therefore, to achieve our objectives, we analyzed for TDP stored samples that had been filtered through 0.45 um filters and used results for runoff DRP and total P from previously conducted analyses. The first trial assessed effects of no gypsum and three rates (560, 1120, and 2240 kg ha^{-1}) of finely ground or granulated gypsum were applied to a low-testing soil with or without fertilizer P application (50 kg ha^{-1}). Two other treatments were runoff events within 48 hours or 15 days after the application, and there were three replications.

Since the trial showed no difference between the powdered or granulated gypsum sources on any runoff P fraction, for the second trial at a different site only granulated gypsum was used. Also, since the soil at this new site tested very high in P, the same gypsum treatments were applied alone or together with the same fertilizer P rate applied the first year. As in the first year, the materials were applied to soybean residue without incorporation into the soil using similar runoff events, and there were three replications.

Table 10 shows average results across both trials, gypsum sources, gypsum application rates, and runoff events since there were no gypsum rate effects on runoff P and the other treatments did not interact with the gypsum rate. There were no statistically significant effects ($P \leq 0.05$) of gypsum application with or without P fertilizer application at the same time on DRP, TDP, and total P concentrations or losses. As expected, runoff P was much higher when P fertilizer was applied with or without gypsum compared with a control without P fertilizer or gypsum application. As was found before for other data sets, the DRP underestimation of TDP loss was the largest without P fertilization (42%) than with P application (12%).

Table 10. Effects gypsum applied with or without P fertilizer on surface runoff P.

Treatment	Dissolved reactive P	Total dissolved P	Total P
---------------------------------- Runoff P Concentrations (mg L^{-1}) ----------------------			
P only	6.39a	7.10a	9.91a
P with Gypsum	9.18a	9.80a	12.09a
Gypsum	0.46b	0.53b	1.65b
None	0.26b	0.72b	1.32b
--------------------------------------- Runoff P Losses (g ha^{-1}) ----------------------------			
P only	435a	494a	648a
P with Gypsum	498a	561a	670a
Gypsum	23b	27b	88b
None	14b	37b	69b

† Numbers with different letters for each column and measurement differ at $P \leq 0.05$.

Therefore, results for gypsum applied to fertilized soils testing low or high in P showed even lesser effects on runoff P loss than was shown in the study referred to above when gypsum was mixed with poultry manure. This was an important result since some claim that gypsum additions at high rates reduces dissolved P loss with surface runoff in Iowa soils.

Cover crops.

To achieve this study objective of comparing DRP and TDP for the cover crop practice we used DRP data and runoff samples from at the time ongoing (2015 to 2019) INRC-funded long-term experiment. The experiment used 12 small watersheds (0.61 to 1.22 ha) to study N and P loss with surface runoff as affected by cover crops (cereal rye or none) and tillage systems (no-till and chisel-plow/disk tillage) in corn-soybean rotations with one crop was present each year (four treatments and three replications). This study measured runoff DRP and total P but not TDP. Results across the five years showed that use of a cover crop with or without tillage reduced losses with runoff of soil, runoff flow, DRP, and total P, and that no-till also reduced all four measurements with or without a cover crop. Due to budget constraints for our study, we analyzed for TDP stored runoff samples filtered through 0.45 um filters from four runoff events in which there was measurable surface runoff from all treatments and replications (two events in 2015, one in 2016, and one in 2018). By using the provided matching DRP concentrations and runoff flow for each watershed for these four events, we calculated TDP loss for each of the four treatments, the average additional TDP loss compared to DRP loss for each event, and applied these calculated proportions to the average DRP results from the 5-year study. Results for runoff P concentrations are not shown because there were no statistically significant ($P \leq 0.05$) main effects of tillage, cover crop, or interactions.

Table 11 shows the annualized (5-year averages) DRP and total P losses from the complete study as well as the comparable estimated TDP losses based on our analyses. Surface runoff was the largest for tillage and no cover crop (58 mm) and the lowest for the other three treatments (33 to 41 mm) which did not differ. Use of a cover crop and no-till reduced losses of all runoff P fractions. Calculations from Table 11 indicate that compared with tillage without a cover crop, reductions of DRP losses were 12% by no-till without a cover crop, 21% by no-till with a cover crop, and 26% by tillage with a cover crop. Similar calculations showed that the estimated reductions of TDP loss from tillage without a cover crop were 3% by no-till without a cover crop, 19% by no-till with a cover crop, and 24% by tillage with a cover crop whereas reductions of total P loss were 38% by no-till without a cover crop, 51% by no-till with a cover crop, and 51% by tillage with a cover crop. Calculations from Table 11 indicate that the annualized DRP underestimation of TDP loss was not affected ($P \leq 0.05$) by the tillage system or use of the cover crop (22 to 29%).

Table 11. Annualized 5-year average effects of tillage systems and cover crops on runoff P and runoff losses.

Cover Crop Treatment	Tillage	No-Till	Means
---------------- Dissolved-Reactive P (g P ha^{-1}) ----------------			
Cover crop	208b†	222a	215b
No cover crop	283a	250b	266a*
---------------- Total-Dissolved P (g P ha^{-1}) ----------------			
Cover crop	277b	296b	287b
No cover crop	364a	352a	358a
---------------- Total P (g P ha^{-1}) ----------------			
Cover crop	389b	386b	387b
No cover crop	792a	489a	640a*
---------------- Runoff Depth (mm) ----------------			
Cover crop	33b	36a	35b
No cover crop	58a	41a	50b*

* Significant difference between tillage systems at $P \leq 0.05$.
† Numbers with different letters for each column and measurement differ at $P \leq 0.05$.

Prairie filter strips.

Filtered runoff samples were provided for this study by Dr. Matthew Helmers from two field-scale watershed studies. One was a long-term experiment at the Neal Smith National Wildlife Refuge, in which treatments for no-till corn-soybean rotation over time with four prairie filter strips designs and no prairie filter strips with three replications. Phosphorus fertilizer (50 kg P ha^{-1}) was applied to all treatments only before corn. For our study we used runoff from the last three years (2013, 2014, and 2015) and only from three treatments, which were prairie strips in 10 or 20% of each watershed and no filter strips. The other study was developed at four fields also and replicated treatments were filter strips or no filter strips also for no-till corn-soybean rotations. This study began in 2017 but there was no measurable runoff because was a dry year, so we could use runoff only from 2018. Results of DRP and stored runoff samples filtered through 0.45 um filters were provided to us so we could analyze them for TDP. At the time of writing this report runoff total P and runoff flow were not available for most sites and years so only DRP and TDP concentrations are shown.

Table 12 shows average runoff DRP and TDP and statistics separately for the Neal Smith experiment and for the simpler study conducted at four sites in 2018.

Table 12. Dissolved reactive P (DRP) and total dissolved P (TDP) concentrations in surface runoff in two studies with or without perennial prairie filter strips.

Experiment	Treatment	DRP	TDP	DRP Proportion of TDP
		P Concentration (mg L^{-1})		---------- % ----------
Neal Smith	No strips	0.29a	0.39a	74a
	With strips	0.40b	0.47b	86b
2018 trials	No strips	0.35a	0.72a	49a
	With strips	0.60b	0.92b	66b

† Numbers with different letters for each column of each study differ at $P \leq 0.05$.

Data shown for the Neal Smith experiment are averages across the three years for the no filter strip treatment and two filter strips treatments. Data shown for the 2018 study are averages are across the four fields for both treatments. Results were similar for both studies in that use of filter strips increased both DRP and TDP concentrations in runoff. The increases were relatively more at the Neal Smith study (72 and 84%, respectively) than at the 2018 study (59 and 78%, respectively), and the average increase across both studies was 65% for DRP and 81% for TDP. The DRP concentration underestimated dissolved P compared with TDP concentration in both studies and for both treatments, but the underestimation was slightly larger without filter strips than with filter strips (38 and 24% on average across both studies).

The consistent result that use of filter strips increased the concentration in runoff of both dissolved P measurement and slightly reduced the DRP underestimation of TDP cannot be fully explained because runoff total P concentration, runoff volume, and losses of all P fractions are not available at this time. Published results for previous years of the Neal Smith study showed that the filter strips drastically reduced soil loss and total P loss but did not affect runoff (Zhou et al., 2014). Therefore, the results observed for runoff P concentrations in our study likely would be approximately similar for P losses.

Summary of Results

Several P, soil, and crop management practices for corn-soybean rotations influenced in different ways P loss with surface runoff and the DRP, TDP, and bioavailable P proportions of the total P loss.

Dissolved P runoff fractions and total runoff P.

- The measurement of dissolved P in surface runoff by the common dissolved reactive P (DRP) by the standard colorimetric method after filtering through a 0.45 um filter underestimated dissolved P in runoff and, therefore, makes the particulate P portion larger than should be.
- Measuring total dissolved P (TDP) or bioavailable P (BAP) provided similar estimates of readily available runoff P and larger than DRP.
- Across all runoff samples in which all runoff P fractions were measured, the mean DRP, TDP, BAP, and total P concentrations were 3.10, 3.67, 3.66, and 5.09 mg L^{-1}, respectively, so DRP, TDP, and BAP were 61, 72, and 72% of the total P. The DRP did not measure 16% of the TDP or BAP.
- Therefore, both TDP and BAP had a similar capacity to assess P readily available to algae not measured by DRP, but the TDP measurement is much less labor intensive than BAP.

Soil-test P (STP).

- Runoff DRP, BAP, TDP, and total P increased with increasing STP and the proportions of DRP, TDP, and BAP of total runoff P also increased as STP increased, although with high variability. However, the DRP/TDP ratio did not correlate to STP.
- Relationships between DRP in runoff with STP measured by the three routine methods Bray-1, Mehlich-3, and Olsen and by soil water-extractable P (WEP), all with colorimetric measurement of extracted P, were linear, although the strength of the relationships was similar for the three routine tests (r^2 0.42 or 0.45) and slightly better for WEP (r^2 0.56).
- Relationships between TDP and STP also were linear, but their strength was poorer than for DRP (r^2 0.24 to 0.25 for the routine test methods and r^2 0.36 for WEP). Therefore, WEP was slightly better than the routine tests to estimate runoff dissolved P. A slightly better relationship between DRP and STP than for TDP and STP may be explained by the similar and only measured P form in extracts by DRP and STP (orthophosphate, using a similar colorimetric method).
- The runoff DRP and TDP concentrations increased with the soil P saturation, but the strength of the relationships was similar to those observed for the routine soil P tests.

Phosphorus application rate.

- A P rate of 25 kg P ha^{-1} across tillage systems and crops increased very little all runoff P fractions compared with no P application, but a rate of 50 kg P ha^{-1} greatly increased all runoff P fractions.
- The DRP and TDP proportions of the total P greatly increased as the P rate increased but DRP/TDP ratio was not correlated with the P rate).

Tillage system and crop interactions.

- On average runoff flow was higher with no-till than with tillage, but this ranking varied greatly for individual years. More runoff with no-till than with tillage has been observed before and has been attributed to soil compaction or poor residue cover.
- The losses of runoff DRP, TDP, BAP, and total P were greater with no-till than with tillage for both crops and were higher in the corn year (planted on soybean residue) than in the soybean year (planted on corn residue) with both tillage systems.
- The proportions of total P loss comprised by DRP, TDP, and BAP were higher with no-till (68, 82, and 75%, respectively) than with tillage (41, 53, and 52%) and were not affected by the crop.
- The DRP underestimation of TDP loss was larger with tillage (24%) than with no-till (16%) only in the soybean year (planted on corn residue.

Tillage system and P source interactions.

- Runoff flow was not affected by the P source (fertilizer, solid poultry manure, liquid swine manure) but as was observed in experiments comparing tillage and crops it was slightly higher with no-till.
- Effects of the P source on runoff P loss varied with the tillage system.
  - With no-till, DRP, TDP, and BAP losses were higher for fertilizer than for the two manures (which did not differ probably because liquid manure was injected) but the total P loss was the lowest for solid poultry manure. With tillage, however, a remarkable result was much lower runoff DRP, TDP, BAP, and total P losses for poultry manure than for fertilizer and swine manure.
  - Greater P loss for solid poultry manure with no-till than with tillage may be explained by more effective removal of P by rainfall from solid manure laying on the soil surface.
- The P source effects on DRP, TDP, and BAP proportions of the total P varied with the tillage system.
  - With tillage, solid poultry manure resulted by in the far smallest DRP, TDP, and BAP proportions of the total P loss (14, 22, and 26%, respectively), and their proportions did not differ for fertilizer and swine manure (on average 48% for DRP, 58% for TDP, and 58% for BAP). With no-till, the DRP, TDP, and BAP proportions of the total P loss were the highest for fertilizer (75, 82, and 86%, respectively) and did not differ for the manures (on average 57, 68, and 69%).
- The DRP underestimation of TDP loss was slightly higher with tillage than with no-till (on average 23 and 14% with tillage and no-till, respectively) and much smaller for fertilizer and liquid swine manure (on average 11 and 16%, respectively) than for solid poultry manure (28%). More runoff dissolved simple organic P forms with tillage and solid poultry manure may explain these results.

Alum and gypsum soil amendments.

- Alum mixed with solid poultry manure drastically reduced runoff DRP, TDP, and BAP compared with untreated manure. For untreated manure the proportion of the total P loss comprised by DRP, TDP, and BAP was 43, 58, and 57%, respectively. Alum reduced the proportion of DRP, BAP, and TDP to 25, 42, and 40%, respectively. Dissolved P loss not accounted for by DRP but measured by TDP was 26% for untreated manure and 40% for alum-treated manure, for reasons not understood.
- Gypsum mixed with poultry manure reduced DRP, TDP, or BAP losses only slightly and the reductions did not reach statistical significance.
- Gypsum applied together with P fertilizer to soil testing low in P or applied alone or together with P fertilizer to soil testing very high in P did not affect DRP, TDP, or total P losses.

Cover crops.

- Runoff in corn-soybean rotations was the largest for tillage without a cereal rye cover crop and the lowest (and statistically similar) for tillage with cover crop and no-till with or without a cover crop.
  - Compared with tillage without a cover crop, the practices no-till without a cover crop, no-till with a cover crop, and tillage with a cover crop reduced DRP loss by 12, 21, and 26%, respectively; reduced TDP loss by 3, 19, and 24%, respectively; and reduced total P loss by 38, 51, and 51%, respectively.

- The DRP underestimation of TDP loss was not affected by the tillage system or use of the cover crop and ranged from 22 to 29%.

Prairie filter strips.

- Use of filter strips increased the DRP and TDP concentrations in surface runoff by 65% for DRP and 81% for TDP.
- The DRP underestimation of the TDP concentration was slightly larger without filter strips (38%) than with filter strips (24%).

CONCLUSIONS

The study demonstrated that the commonly used measurement of dissolved-reactive P in runoff often underestimates total dissolved P and bioavailable P losses. Across all runoff samples analyzed, dissolved reactive P, total dissolved P, and bioavailable P were 61, 72, and 72 % of the total P, respectively. Therefore, total dissolved P was greater than dissolved reactive P and similar to bioavailable P, and 16% of the total dissolved or bioavailable P was wrongly considered particulate P. The dissolved and bioavailable P forms in runoff not measured by the dissolved reactive P measurement also are very effective at encouraging rapid eutrophication of surface water resources.

The several P, soil, and crop management practices for corn-soybean rotations included in the study influenced in different ways the proportion of the total runoff P comprised by dissolved and bioavailable P forms, however. Increasing soil-test P, soil P saturation, or the P application rate greatly increased the proportions of dissolved reactive and total dissolved P in runoff, but did not affect the dissolved reactive P underestimation of the total dissolved P. No-till management increased the proportion of the total runoff P loss comprised by dissolved and bioavailable P compared with tillage, these were higher in the corn year (planted on soybean residue) than in the soybean year (planted on corn residue) with both tillage systems, and the dissolved reactive P underestimation of the total dissolved P loss was slightly larger with tillage than with no-till mainly in the soybean year (planted on corn residue). The P source effects on runoff P varied with the tillage system. With tillage, the proportion of the total P comprised by dissolved and bioavailable P were the smallest for poultry manure and the largest for fertilizer and swine manure but with no-till were the highest for fertilizer and did not differ for the two manures. The dissolved reactive P underestimation of dissolved P loss much smaller for fertilizer and liquid swine manure than for solid poultry manure. Of alum and gypsum amendments, only alum significantly reduced the proportion of the total runoff P loss comprised by dissolved and bioavailable P and increased the underestimation of dissolved P by the dissolved reactive P measurement. Use of a winter cereal rye cover crop reduced dissolved and total runoff P loss with tillage and no-till management, but the reductions were much larger with tillage, and the cover crop did not affect the dissolved reactive P underestimation of dissolved P loss. In contrast, use of filter strips increased dissolved reactive P and dissolved P concentrations in surface runoff but slightly decreased the dissolved reactive P underestimation of the total dissolved P concentration.

Overall, the study demonstrated that some management practices that have been proved to reduce soil and total P loss with surface runoff may also decrease dissolved and bioavailable P losses. Others, however, actually increase the proportion of the total P loss comprised by these runoff P forms or, worse, increase the losses, and also increase the underestimation of dissolved P by the commonly used dissolved reactive P measurement. Different soil, rainfall (by affected runoff flow), and management practices often interacted in complex ways to mediate these effects. The study also demonstrated that measuring runoff total dissolved P directly on runoff filtered through 0.45 um filters by ICP was as effective as the more expensive measurement of total dissolved P after digesting filtered runoff samples to transform all dissolved P forms into the orthophosphate P forms, and most often total dissolved P was similar to the much more labor-intensive runoff bioavailable P measurement. This result is of much importance because the easier and less costly ICP total dissolved P measurement can be easily and rapidly introduced in research or surveys of runoff P loss.

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