Management of fertilizer, manure, tillage, cover crop, and alum or gypsum soil amendments to minimize dissolved P loss from corn and soybean fields

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Introduction

Excess phosphorus (P) delivery to water bodies via surface runoff results in excess algae growth that impairs water quality to undesirable levels. Usually measured runoff P fractions in research or monitoring 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 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. 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. Previous Iowa research showed higher dissolved P loss with fertilizer than with manure and that some conservation practices which 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 commonly used DRP analysis 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 colorimetry or inductively-coupled plasma (ICP) methods. The ICP has also been used to measure P in filtered or centrifuged soil extracts, and test results are higher than with colorimetry 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dissolved P in filtered extracts has been shown to be mainly dissolved organic P forms (Mallarino and Borges, unpublished) but sometimes also colloidal-sized inorganic or organic P forms that quickly decompose or hydrolyze to forms immediately available to algae. Therefore, the low-cost ICP analysis could be used to analyze filtered runoff for total dissolved P.

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, and to better consider runoff dissolved P in the Iowa Nutrient Reduction Strategy. This article summarizes recent research that evaluated the impacts of several P, crop, and soil management practices on the proportion of the total runoff P comprised by dissolved P fractions.

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. The experiments were conducted under natural rainfall (in small watersheds or large plots) or by using simulated rainfall in small field plots. The watershed field-scale studies used H-flumes and automatic runoff monitoring and sampling equipment or a tipping-bucket runoff monitoring and sampling system. The field rainfall simulations were conducted with a portable rainfall simulator built based on a design suggested by the National Phosphorus Research Project (SERA-17, 2002).

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 (6-inch 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.

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 0-2 and 2-6 inches but only results for the top 2 inches are shown because previous research demonstrated that with no-till management soil P from this depth often relates better with dissolved P loss with runoff than samples taken from a 6-inch depth. Soil was analyzed for Bray-1 P, Mehlich-3 P, and Olsen P following procedures recommended by the North Central Extension and Research Committee for Soil Testing and Plant Analysis (NCERA-13) and for water-extractable P (WEP) all with the standard colorimetric measurement of extracted P. Soil extractable Al, Ca, and Fe were measured with the Mehlich-3 extractant to estimate degree of soil P saturation (DPS) by two commonly used methods [using extracted calcium (Ca) and P or extracted aluminum (Al), iron (Fe), and P)], which will be referred to as DPSCa and DPSAlFe, respectively (Khiari et al., 2000; Maguire and Sims, 2002; Kleinman et al., 2002).

Total P of unfiltered runoff samples was analyzed by the alkaline-oxidation digestion procedure utilizing sodium hypobromite and P in the digests was measured colorimetrically (Murphy and Riley, 1962). Runoff samples were filtered through 0.45-um filters and P in 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 also was digested to transform all present dissolved P to the orthophosphate form and the P was measured colorimetrically 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.

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 DPS_{Ca} ranged from 0.5 to 19% and for DPS_{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) by the three routine P tests, Bray-1, Mehlich-3, and Olsen since there were few strongly calcareous soils (not shown). The relationships between WEP and the routine tests also were linear with lower r^2 values of 0.69 to 0.78 (not shown). The poorer relationship between each routine soil P test and WEP is well known, and WEP is not 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 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 (2-inch 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 $(P_{M3}/Ca_{M3}) \times 100$.

‡ $DPS_{(Al + Fe)}$), degree of P saturation by $[P_{M3}/(Al_{M3} + Fe_{M3})] \times 100$

Measurement of runoff total dissolved P

Although many studies have proved that in soil P extracts measuring dissolved reactive P 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. An important objective of this study was to assess runoff dissolved P not measured by DRP on many runoff samples so we chose to do it using the lower-cost direct ICP measurement, but felt necessary to demonstrate its effectively. 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 Figure 1 demonstrates that runoff TDP measured on filtered samples directly by ICP is equivalent to the total P measurement after digesting the filtered samples. This is of practical importance because the ICP measurement is much easier and less costly than a digestion followed by P measurement.

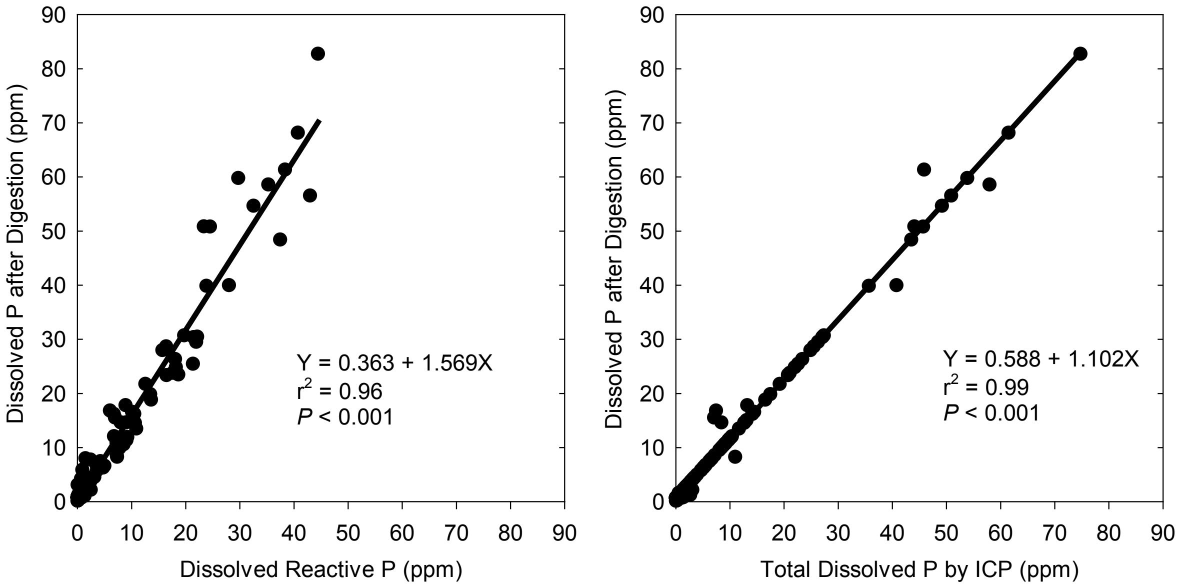

Figure 1. Relationship between dissolved runoff P concentration measured after digesting filtered samples and concentrations of dissolved-reactive P or total dissolved P without digestion.

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 ppm, respectively) indicate that on average DRP did not measure 14% of TDP (1.79 and 2.19 ppm, respectively). Therefore, DRP underestimates dissolved P in runoff and makes the sediment bound (particulate P) portion larger than should be. Previous research with soil or drainage extracts has shown that the additional dissolved P measured by ICP compared with the DRP method include mainly simple organic P forms (Rowland and Haygarth, 1997; Mallarino and Borges, unpublished).

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

Measurement	Minimum	Maximum	Median	Mean	Samples
	--------------------	*Concentrations (ppm)*	------------------		
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
Total P	0.13	61.7	2.08	4.55	728
Particulate P from Total P - DRP	0	25.7	0.96	1.77	728
Particulate P from Total P - TDP	0	28.4	0.60	1.19	728
Total solids (TS)	0.01	16,850	570	958	607

Figure 2 shows that relationships among the concentrations of runoff P fractions across all samples were linear and were the strongest among DRP and TDP. 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 or TDP were weaker. The relative concentration of DRP and TDP fractions calculated as their ratio was not correlated with total runoff P (not shown).

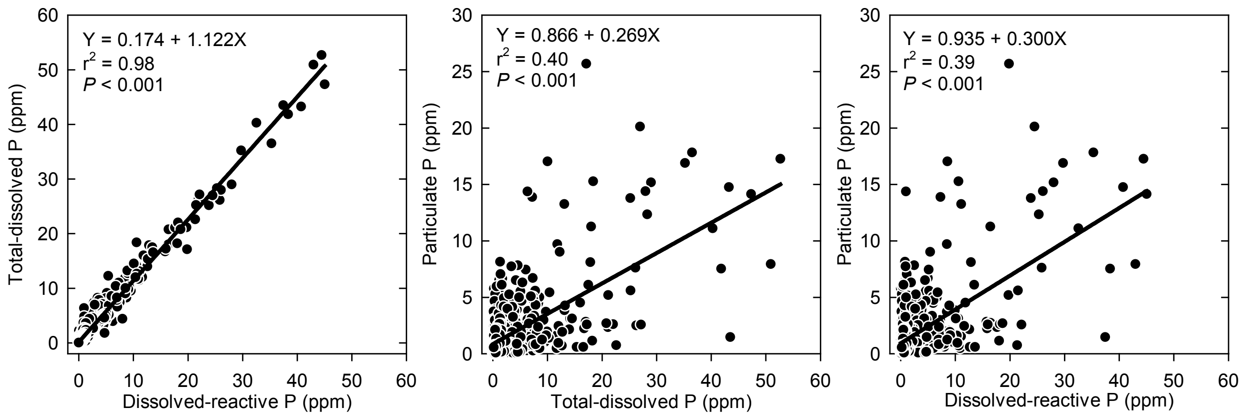

Figure 2. Relationships among concentrations of three runoff P fractions.

Relationships between soil-test p and surface runoff p fractions

Figure 3 shows relationships between STP measured by the Mehlich-3 test and WEP with runoff DRP or TDP concentrations for soils not fertilized since the last soil sampling. The strength of relationships for the Bay-1 and Olsen methods were similar to the Mehlich-3 (not shown). Extensive previous research has shown that applying P since the last soil sampling very often erase any relationship between STP and the loss of all runoff P fractions. The relationships for DRP were linear and with approximately similar strength for the three routine STP methods (r^2 0.42 or 0.45) but the relationship for WEP was stronger (r^2 0.56). Relationships for TDP also were linear but poorer than for DRP, and were r^2 24 or 25 for the routine tests and r^2 0.36 for WEP. Reasons for slightly better relationships between DRP and STP than for TDP and STP might be that the additional dissolved P forms other than orthophosphate by TDP do not have an exact match with STP since measured soil extracted P was only orthophosphate by the colorimetric. Relationships between STP and particulate P or total P concentrations in runoff (not shown) also were linear but much poorer (r^2 0.01 to 0.10), which agrees with expectations.

Figure 4 shows that 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. 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 Figure 4 are similar to r^2 for relationships between DRP concentration and STP by the routine tests in Figure 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.

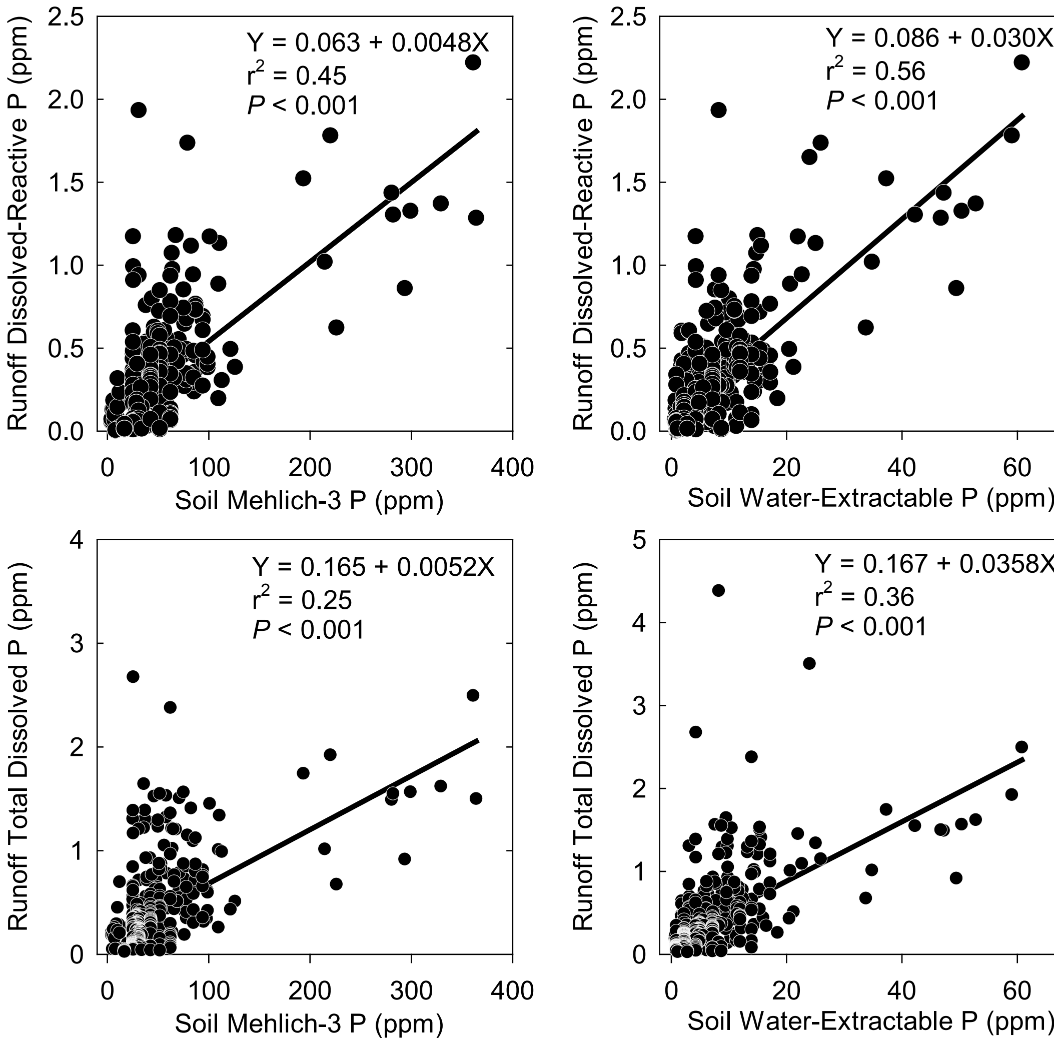

Figure 3. Relationships between soil-test P by four methods and runoff dissolved reactive P or total dissolved P for soils receiving no P since soil sampling.

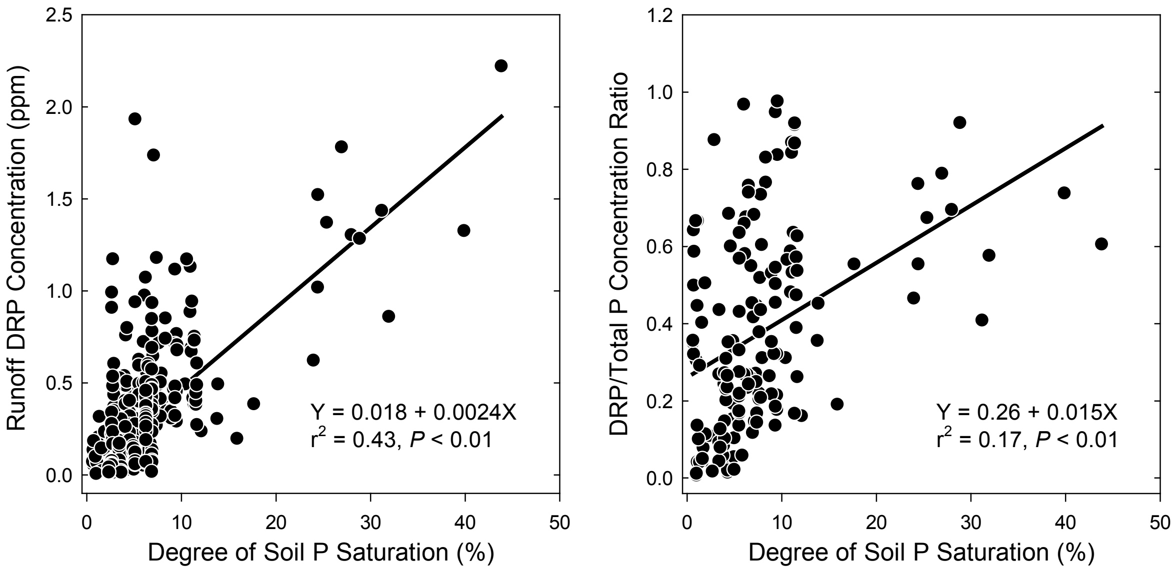

Figure 4. Relationships between runoff dissolved reactive P concentration (DRP) or the DRP/total P concentration ration and two estimates of soil degree of P saturation.

Figure 5 shows relationships for the total P/DRP concentrations ratio and the particulate P/DRP concentrations ratio with STP by either WEP or the Mehlich-3 routine method. The graphs for the Mehlich-3 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 graphs for WEP and for particulate P/DRP and total P/DRP ratios show similar trends, but for the overall lower typical WEP values. Similar trends were observed for the Bray-1 and Olsen soil P 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 at high STP values the dissolved P loss increases sharply.

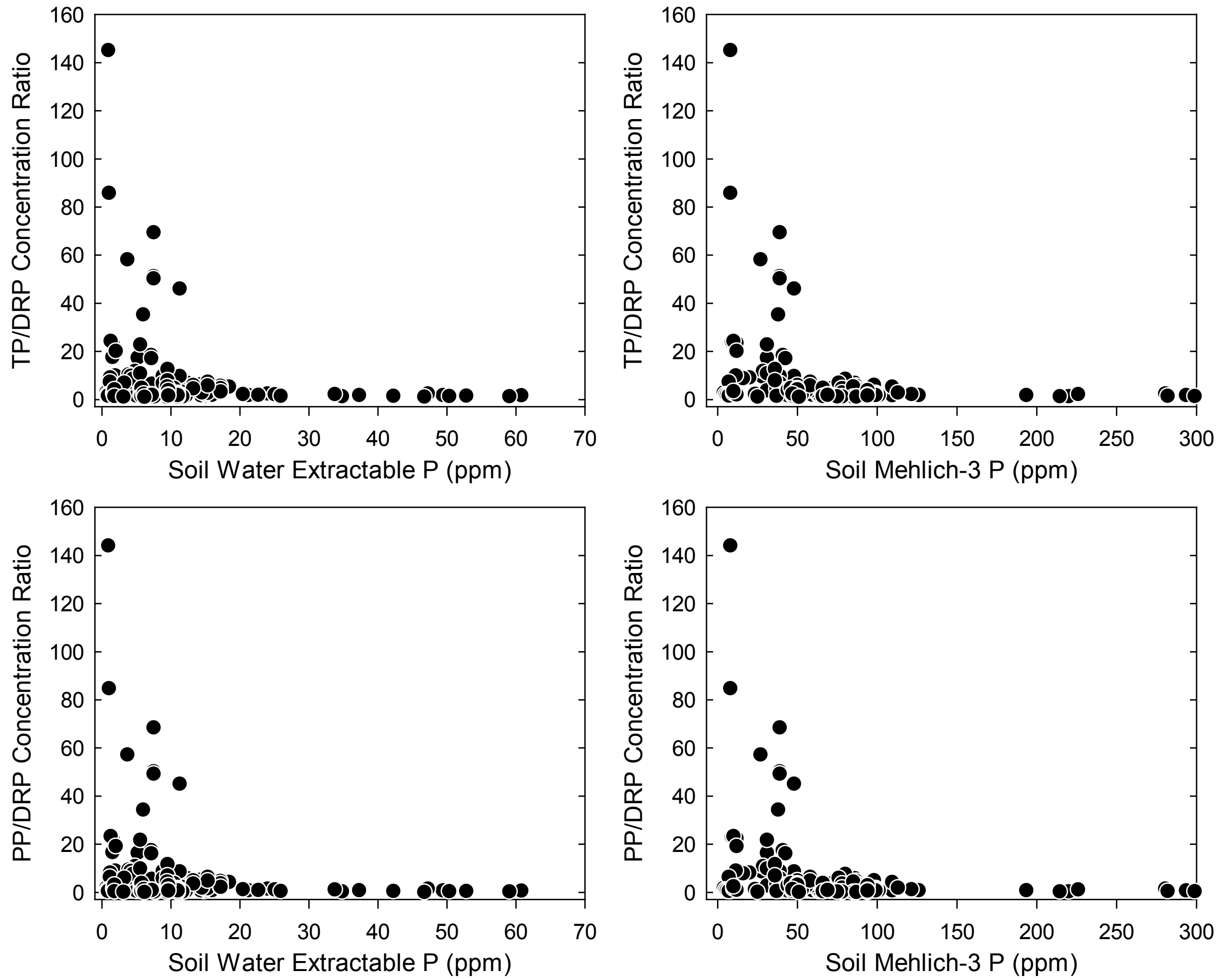

Figure 5. Relationships between the total P (TP) or particulate P (PP) ratio to dissolved reactive P (DRP) with water-extractable or Mehlich-3 soil P (no P applied since the soil sampling).

Management effects on runoff dissolved P fractions

Phosphorus P application rate.

Table 3 shows effects of the P application rate for corn and soybean across P sources on runoff DRP, TDP, and total P concentrations and losses. The P rate did not affect runoff flow (not shown). There was a very large effect of the highest P rate applied (100 lb P_2O_5/acre) and a much lower effect of the 50-lb rate on runoff P concentrations and losses. The 50-lb rate is about the annual P rate needed to maintain optimum STP for corn and soybean. The 100-lb 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 3. Effect of the P application rate on the concentrations and losses of several runoff P fractions (means across experiments, sites, and replications).

	Phosphorus Application Rate (lb P_2O_5/ha)					
Runoff P Fraction	**0**	**50**	**100**	**0**	**50**	**100**
	-- P Concentrations (ppm) --			*------- P Losses (g/ha) -------*		
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

† Different letters within each row for concentrations or losses indicate significant differences at P ≤ 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 that 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 and total P from previously conducted analyses. The results are shown across all studies, years, and replications.

Table 4 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, and total P. 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 and TDP 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. On average across years, runoff in the corn year (planted on soybean residue) was 0.5 and 0.57 inches with tillage and no-till, respectively, and in the soybean year (planted on corn residue) was 0.52 and 0.61 inches with tillage and no-till, respectively. Therefore, runoff was slightly more in the soybean year with both tillage systems and was higher with no-till for both crops. In a previous 6-year study (Mallarino et al., 2013) there was no overall tillage or crop effects 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 these experiments. Some expect always more runoff with tillage than with no-till, but the temporal variation and more runoff we found for no-till is common, which has been attributed to more soil compaction with no-till (mainly due to wheel traffic) and variable residue cover between systems when moldboard plowing is not used for the tillage (Voorhees and Lindstrom, 1983; Lindstrom and Onstad, 1984; Benoit and Lindstrom, 1987). Soil compaction and residue cover were not measured in these experiments.

Table 4. 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 treatment	P Concentrations (ppm)			P Losses (g/ha)		
	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*
	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 $P \leq 0.05$.

Results for the runoff P loss in Table 4 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. 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. Proportionally, the differences for all runoff fractions were greater with tillage than with no-till. Calculations from data in Table 4 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.

The crop did not affect significantly the proportion of the total P loss comprised by DRP and TDP. 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 and TDP losses of the total P loss was 68 and 75%, respectively, whereas with tillage the proportions were only 41 and 53%, respectively.

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, 50, or 100 lb P_2O_5/acre).

Table 5 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. This result for tillage effects agrees with tillage effects shown before. On average across trials and years, the runoff was slightly higher for no-till (0.67 inches) than with tillage (0.63 inches) and was not affected by the P source. 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-till, DRP, TDP, and total P concentrations were higher for fertilizer than for the two manures, and the manures clearly differed only for total P with lower concentrations for solid poultry manure. With tillage, however, a most remarkable result was much lower DRP and TDP concentrations for poultry manure than for fertilizer and swine manure, which did not differ, and no P source differences for total P. Results for P losses were approximately similar since the runoff flow did not differ consistently among the P sources. The DRP and TDP losses for poultry manure were so low that statistically did not differ from the no P control. It is noteworthy that the relative tillage differences for liquid swine manure were consistently smaller than for the other two sources for all runoff P fractions, which may be explained by injection of the manure into the soil with or without tillage.

Table 5. Runoff P concentrations and losses as affected by tillage and the P source across sites where these practices were compared.

	P Concentrations (ppm)			P Losses (g/ha)		
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*
	------------------- *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 $P \leq 0.05$.

Calculations from data in Table 5 show that with no-till, the DRP and TDP proportions of the total P loss were the highest for fertilizer (75% for DRP and 82% for TDP) and did not differ for solid poultry manure and liquid swine manure (on average 57% for DRP and 68% for TDP). With tillage, however, solid poultry manure resulted in far the smallest DRP and TDP proportions of the total P loss (14 and 22%, respectively) compared with fertilizer and swine manure (on average 48% for DRP and 58% for TDP). The finding that dissolved P losses for solid poultry manure with tillage were so much lower than for the other sources (and statistically similar to losses from the no P control) is very important, and could 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 it is incorporated into the soil.

The underestimation of dissolved P loss by DRP (compared with TDP) was slightly higher with tillage than with no-till (on average across 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

Data used for this section are from two different field rainfall simulation studies. One study evaluated effects of alum or gypsum mixed with solid egg-layers poultry manure on runoff P loss at three different sites in three different years. The materials were applied to soybean residue in the fall with or without incorporation into the soil. Two other treatments were runoff events within 2 or ten days after the application and there were three replications. The manure was applied at 100 lb P_2O_5/acre and amounts of alum or gypsum were 844 and 712 lb/acre.

Table 7 shows average results across tillage and runoff events. Runoff volume was not affected (not shown). Alum mixed with poultry manure greatly reduced DRP and TDP runoff concentrations and losses compared with the untreated manure and to levels statistically comparable to the control receiving no P or alum but did not affect total P (apparent reductions are not significant at $P \leq 0.05$). On the other hand, runoff P reductions by mixing gypsum with the poultry manure were much less than for 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 broiler litter drastically reduced dissolved P loss with surface runoff.

Table 7. Effects of alum and gypsum applied with poultry manure on surface runoff P.

Treatment	Dissolved reactive P	Total dissolved P	Total P
	--------------------- *Runoff P Concentrations (ppm)* ---------------		
No P, no alum	0.20b†	0.35b	1.47b
Manure alone	1.10a	1.50a	2.84a
Manure + alum	0.48b	0.78b	2.09ab
Manure + gypsum	0.83a	1.35a	2.33a
	--------------------------- *Runoff P Losses (g/ha)* --------------------		
No P, no alum	30c	52c	161b
Manure alone	155a	209a	360a
Manure + alum	69bc	114bc	271ab
Manure + gypsum	94ba	178ab	261ab

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

Calculations from Table 7 indicate that 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%). Therefore, both alum and gypsum additions to the manure increased the DRP underestimation of dissolved P for reasons not clear at this time. For untreated poultry manure the proportion of the total P loss comprised by DRP and TDP was 43 and 58%, respectively. The mixing of alum with manure drastically reduced the proportion of DRP and TDP to 25 and 40%, respectively. The mixing of gypsum with manure slightly reduced the proportion of DRP (36%) but increased or did not affect the proportion of TDP (68%) of total P, respectively.

The other gypsum study had been recently completed but runoff TDP had not been measured, so we analyzed for TDP stored samples that had been filtered through 0.45 um filters. A first trial assessed effects of no gypsum and three rates (500, 1000, and 2000 lb/acre) of finely ground or granulated gypsum were applied to a low-testing soil with or without fertilizer P application (100 lb P_2O_5/acre). Since the first-year results showed no difference between the powdered or granulated gypsum sources on any runoff P fraction, for a second year at a different site with soil testing very high in P only granulated gypsum was used and the same gypsum treatments were applied alone or together with a similar P rater. The materials were applied to soybean residue without incorporation into the soil, two other treatments were runoff events within 48 hours or 15 days after the application, and there were three replications. Table 8 shows average results across years, gypsum application rates, and runoff events since there were no rate effects on runoff P. There were no statistically significant effects ($P \leq 0.05$) of gypsum application with or without P fertilizer at the same time on DRP, TDP, and total P concentrations or losses. 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 8. 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 $P \leq 0.05$.

Results from both studies were consistent at showing that gypsum application resulted in either very small reduction of runoff dissolved P (DRP or TDP) when mixed with poultry manure or no reduction at all when applied alone or together with P fertilizer in soils testing low or very high in P. Therefore, results for Iowa did not confirm claims that gypsum additions at high rates reduce dissolved P loss with surface runoff.

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 (1.5 to 3 acres) 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 had measured runoff DRP and total P but not TDP. Due to budget constraints, for comparison of DRP and TDP 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. 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 one, and applied these calculated proportions to the average DRP results from the 5-year study.

On average across the 5 years, 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 (Table 9). Surface runoff was the largest for tillage and no cover crop and the lowest for the other three treatments. Use of a cover crop and no-till reduced losses of all runoff P fractions. Calculations data in the table 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. 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 9. Annual 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	1.3b	1.42a	1.38b
No cover crop	2.38a	1.61a	1.97*

* 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 (100 lb P_2O_5/acre) 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, but at the time of writing this article runoff total P and runoff flow were not available for most sites so only DRP and TDP concentrations are shown.

Table 10 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 10. 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 (ppm)		------ % ------
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 and conclusions

Several P, soil, and crop management practices for corn-soybean rotations influenced in different ways the loss of dissolved P fractions, sediment-bound P, and total P with surface runoff.

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 runoff through a 0.45 um filter underestimated the total dissolved P (TDP) by 14% in average across all samples and, as a consequence, underestimates the short-term impact of runoff P on water quality.

Soil-test P (STP) and P rate impacts

Runoff P losses increased with increasing STP and the P application rate, and most importantly the proportion of the total runoff P comprised by dissolved P also greatly increased. However, the DRP underestimation of the total dissolved P did not increase.

The soil P saturation measurement by two methods did not relate better with the loss of dissolved P than did soil-test P. The soil P saturation is more useful in soils of other regions with different properties and much higher soil P levels.

Tillage system and crop interactions

The dissolved P loss and the proportion of the total P comprised by dissolved P were greater with no-till than with tillage, 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 DRP underestimation of dissolved P loss was larger with tillage than with no-till, mainly 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, or liquid swine manure) in these studies.

Effects of the P source on runoff P loss varied with the tillage system

With no-till, DRP, TDP, and total P losses were higher for fertilizer than for the two manures, and total P loss was lower for solid poultry manure. The DRP and TDP proportions of the total P loss were the highest for fertilizer (75 and 82%, respectively) than for the manures (on average 57 and 68%).

With tillage, however, there were much lower DRP and TDP losses for poultry manure than for fertilizer and swine manure and no P source differences for total P. Poultry manure resulted in the far smallest DRP and TDP proportions of the total P loss (14 and 22%, respectively) than for the manures (on average 48 and 58%).

The DRP underestimation of TDP loss was slightly higher with tillage than with no-till (23 and 14%, respectively), and was smaller for fertilizer and liquid swine manure (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 total P losses. For untreated manure, the proportion of the total P loss comprised by DRP and TDP was 43 and 58%, respectively, but alum treatment reduced the proportion of DRP and TDP to 25 and 42%, respectively. The DRP measurement underestimation of TDP was 26% for untreated manure and 40% for alum-treated manure (for reasons not clearly understood).

Gypsum mixed with poultry manure reduced DRP and TDP losses only slightly and the reductions did not reach statistical significance. Gypsum applied together with or without P fertilizer to soils testing low or 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 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%).

Overall, the study demonstrated that some management practices that have been proved to reduce soil and total P loss with surface runoff often increase the proportion of the total P loss comprised by dissolved P and in some cases increase the dissolved P losses. The study also demonstrated that the commonly used runoff dissolved-reactive P measurement often significantly underestimates total dissolved P losses. Different soil, rainfall (by affecting runoff flow), and management practices often interacted in complex ways to mediate these effects. The information provided will be useful to be able to reduce not only total P loss with surface runoff. but also dissolved P loss. The dissolved reactive P fraction and also the additional forms measured by the total dissolved analysis are effective at encouraging rapid eutrophication of surface water resources. The study demonstrated that measuring runoff total dissolved P directly on filtered runoff by ICP accurate and cost-effective and could rapidly introduced in research or surveys of runoff P loss.

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