FINAL REPORT TO THE IOWA NUTRIENT RESEARCH CENTER
PROJECT 2018-18

Phosphorus Placement and Application Time Strategies to Reduce Dissolved P Loss with Surface Runoff in No-Till Corn-Soybean Rotations

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INTRODUCTION

Research, surveys, and the Iowa P Index indicate that dissolved and sediment bound phosphorus (P) forms account for significant proportions in surface runoff. With tillage and high soil erosion, most of the P lost is sediment bound P and, therefore, there has been a major effort in Iowa on reducing soil erosion. For these reasons, the Iowa Nutrient Reduction Strategy estimates of P loss reduction by different management practices emphasized total P loss. Recent research and surveys in Iowa and the Corn Belt indicate, however, that the dissolved P loss from fields is greater than often is assumed. Moreover, Iowa research showed that no-tillage drastically reduces soil and total P loss but may not affect or increase dissolved P loss from corn and soybean fields compared with tillage. The P fertilizer placement method and the timing of application could affect both dissolved and total P loss with no-till management, although research showed that in Iowa subsurface banding compared with broadcast fertilization and applying P in the fall or spring seldom affect crop yield. However, scarce research has compared in a similar experimental setting and with statistical replication how broadcast or subsurface banding of P fertilizer or the application timing affect the proportion and amounts of dissolved P and sediment-bound P lost with or without tillage. New studies will help develop improved BMPs for P fertilizer management to reduce dissolved P loss from fields managed with no-tillage.

Therefore, the objectives of this new study were: (1) Evaluate the impacts of broadcast and subsurface banding of P fertilizer and the timing of broadcast P application on bioavailable and dissolved P loss with surface runoff in corn-soybean rotations managed with no-tillage. (2) Evaluate the impacts of these practices on soil and sediment-bound P loss with surface runoff with no-tillage.

The initial approved proposal was for a two-year study to be conducted from fall 2018 through fall 2020, and funding was received with that purpose. In summer 2020 we submitted a new proposal to continue the study for two more years that was not approved. However, we used funding savings (due to fewer runoff events than expected) and additional unrestricted gift funds to continue the study for a third year, from fall 2020 until fall 2021. Therefore, this final report includes results for the three years of the study.

SUMMARY OF PROCEDURES

The study was conducted under natural rainfall with corn-soybean rotations harvested for grain and managed with no-tillage in a field of the NW Iowa State University Research and Demonstration farm. Soils of the experimental area were Galva and Sac series with silty clay loam texture in the top 15-cm layer. The study used 27 plots measuring 100 by 20 feet, each delimited by earthen berms with a permanent grass sod cover in the upslope and each lateral side that had been established in previous years to avoid receiving runoff from areas outside each plot. The downslope side had installed a removable vertical aluminum wall 0.6-inch thick and 12 inches tall partially buried in the soil to divert the surface runoff to pits having a tipping bucket runoff monitoring and sampling system. Electronic devices recorded every time each side of the tipping bucket discharged one gallon of runoff whereas mechanical devices took samples proportional to the runoff volume.

Six P management systems were evaluated with three replications arranged in a randomized complete block (RCBD) design. The blocks (replications) were designed so each block had the most uniform possible slope, and the average slopes of each block were 2.94, 3.28, and 3.65%. For Systems 1 through 5, each crop of the rotation was present each year on randomized adjacent plots (24 plots). The P application rates attempted to maintain soil-test P between the Optimum and High interpretation categories (Mallarino et al., 2013) by applying either the annual maintenance rate for the rotation or twice this rate only once every other year. For Systems 1 and 2, 50 lb P_2O_5/acre/year was broadcast in the fall or preplant in the spring to both crops (12 plots). For System 3, 50 P_2O_5/acre/year was banded with the planter in the spring to both crops 2 inches below and besides the seeds (6 plots). For Systems 4 and 5, 100 lb P_2O_5/acre were broadcast in the fall every other year before corn or before soybean (6 plots). For System 6 only one crop was planted each year; the rotation was completed over time by planting corn in 2019, soybean in 2020, and corn in 2021; a cereal rye cover crop over-seeded in the fall before each crop grain harvest; and rate of 100 lb P_2O_5/acre was broadcast in the fall only before corn (3 plots).

A previous study at the site had the same annual and biannual (twice the annual rate applied only once every two years) P treatments to the same plots that we continued using for this study. By the fall 2018 soil sampling all plots had received the same amount of P over the last 2-year period (crops in 2017 and 2018); either the maintenance rate each year or twice this amount applied only once every two years. Therefore, it is important to note for appropriate interpretation of the soil-test P and runoff P results that crops of Systems 1, 2, and 3 had the same P rate applied broadcast or banded every year whereas crops of Systems 4, 5, and 6 and 3 had twice that P amount applied for crops of odd years and no P applied for crops of even years.

Granulated triple superphosphate fertilizer (0-46-0) was used for all P treatments, and non-limiting applications of nitrogen (only for corn), sulfur, and micronutrients were applied uniformly across all plots. The fall P treatments were broadcast after each crop and the soil sampling as called for by the experimental design (completely randomized blocks) and before snowfall or soil froze. The spring fertilizer broadcast treatment was applied to plots of System 2 in spring after snowmelt (50 lb P_2O_5/acre). Corn and soybean were planted in late April or early May using a 76-cm row spacing, and for System 3 the P (50 lb P_2O_5/acre) was banded at the same time with planter fertilizer attachments about 5 cm below and besides the seeds. Just before the rye cover crop was terminated with glyphosate herbicide in the spring, aboveground biomass samples were collected for to measure dry matter yield and the plant P that would be recycled to the soil. Corn and soybean were planted 7 to 10 days after the rye termination. Corn and soybean were harvested for grain, and grain samples were analyzed for P concentration to measure P removal with harvest.

Each plot was sampled from depths of 0-2 and 2-6 inches. Soil P was analyzed P by the routine Bray-1, Mehlich-3, and Olsen tests that are used in Iowa for crop production and the Iowa P Index following procedures recommended by the NCERA-13 committee (NCERA-13, 2015) with the standard colorimetric measurement of extracted P (Murphy and Riley, 1962) and by water-extractable P following the method described by Pote et al. (1996). Soil was also analyzed for pH using a 1:1 soil/water ratio and for organic matter by the loss of weight on ignition method (NCERA-13, 2015).

Surface runoff samples from rainfall or snowmelt were collected for each event. The unfiltered runoff samples were analyzed for sediment, total P, and bioavailable P. Runoff total P was analyzed with the alkaline-oxidation digestion procedure utilizing a sodium hypobromite solution (Dick and Tabatabai, 1977) adapted to an aluminum block (Cihacek and Lizzotte, 1990). Runoff bioavailable P (BAP) was extracted by the Fe-oxide impregnated paper method by shaking impregnated paper with 40 mL runoff for 16 hours, removing adsorbed P from the paper by shaking for 1 hour in 30 mL 0.1 M H_2SO_4, and subsequent P colorimetric determination by the Murphy and Riley procedure (Sharpley, 1993).

Runoff sub-samples were filtered through 0.45-micron filters to be analyzed for dissolved reactive P (DRP by the Murphy and Riley colorimetric meth (Murphy and Riley, 1962) and by total dissolved P by inductively coupled plasma (ICP). Previous studies demonstrated measuring P by ICP in extracts filtered through a 0.45-micron filter provides the same results (statistically) than digesting the filtered extracts to change all dissolved P forms (inorganic or organic) to orthophosphate and measuring P by the Murphy and Riley colorimetric procedure (Rowland and Haygarth, 1997; Mallarino et al., 2021a and 2021b).

RESULTS AND DISCUSSION

Soil Test Values

On average across all plots, initial (fall 2018) soil pH and organic matter in the top 15-cm soil layer were 6.32 and 4.05%, respectively. Both pH and organic matter were stratified in the top 15-cm layer, which was expected due to a long-term history of chisel-plow/disk management and of no-till management since 2018. Across all systems and soil sampling dates over three years, soil pH and organic matter were 7.11 and 4.15%, respectively, in the top 5-cm layer and 5.95 and 3.72% in the 5-15 cm layer. Therefore, pH and organic matter were 1.2 and 1.13 times higher in the top 5-cm layer of soil.

Although soil P was measured by three routine tests, only Bray-1 results are shown because other than expected differences in amounts of P extracted by the Olsen method (lower values than for the Bray-1 and Mehlich-3 tests) the soil-test P rankings concerning systems effects or variability at the site were similar. It is important to remember that appropriate P treatments for the new study began to be applied before this study began, but by fall 2018 all plots had received the same amount of P applied either annually or every other year. Therefore, any observable difference in soil-test P among the systems would result either from random variability or experimental errors at the field or laboratory.

Figure 1 shows the initial Bray-1 (Fig. 1A) and water-extractable P (Fig. 1B) values from soil samples collected in fall 2018 between crop harvest and the application of the P treatments later that fall. Test results shown are averages for the two crops of the rotation for each P management system. The Bay-1 soil P levels for a 15-cm depth were within the High interpretation category, which encompasses values from 20 to 30 ppm (Mallarino et al., 2013). The P stratification was significant, and on average Bray-1 P in the top 5-cm of soil was 2.4 times the concentration in the 5-15 cm layer. Water-extractable P (WEP) (Fig. 1B) was much lower than Bray-1 P, and in general the tests rankings for the systems and sampling depths were similar. The WEP levels were 2.6 higher in the top 5-cm depth than in the 5-15 cm subsurface layer. There were no statistically significant differences for any test or depth, but different amounts of P in top 5-cm depth by the Bray-1 or WEP tests for System 6 (managed with a cereal rye cover crop) in relation to the other systems is potentially important for water quality. Bray-1 P for System

6 was approximately similar to the other systems, but WEP was the lowest of all systems. Organic matter and extractable Ca in top 5-cm of soil was higher for System 6 (4.40% and, 4873 ppm) than for the other systems (4.07-4.23% and 4512-4709 ppm) and there were no clear differences for pH, Al, Ca, and Fe (not shown). Perhaps the slightly higher Ca and organic matter in the topsoil with a cover crop retains P forms that the routine tests solutions can extract.

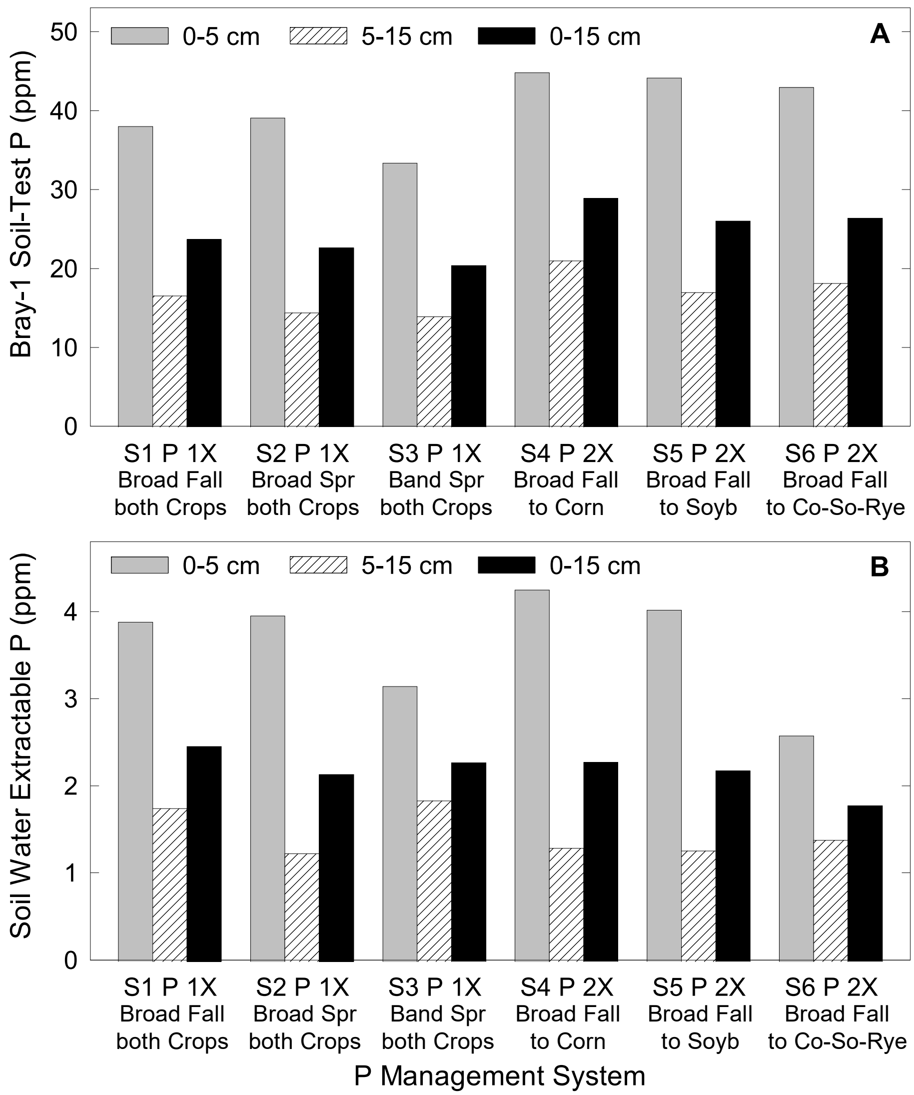

Fig.1. Initial Bray-1 (A) and water-extractable P (B) in fall 2018 for all systems (S1 to S6). 1X, annual rate of 50 lb P_2O_5/acre applied to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band); 2X, 100 lb P_2O_5/acre applied once every other year before corn, soybean, or either crop with a rye cover crop (Co-So-Rye). There were no statistically significant differences for any test or depth ($P \leq 0.10$).

Figure 2 shows results for the Bray-1 and WEP in soil samples collected between crop harvest and the P treatment applications in fall 2019, one year after the study began. It is important to note that all the 1X (annual) P treatments (1X) were applied for the 2019 crop year either in fall 2018 or spring 2019, but none of the broadcast fall 2X (twice the annual amount every two years) P treatments were applied in fall 2018 because had been applied in fall 2017. There were no statistically significant Bray-1 P differences ($P \leq 0.10$) among the systems for any sampling depth (Fig. 2A). The only obvious and potentially important difference for water quality was that the level for System 3 at the 5-cm depth was the lowest among the systems and the level at the 5-15 cm depth was intermediate compared with the others. This can be explained by the subsurface band P application for System 3.

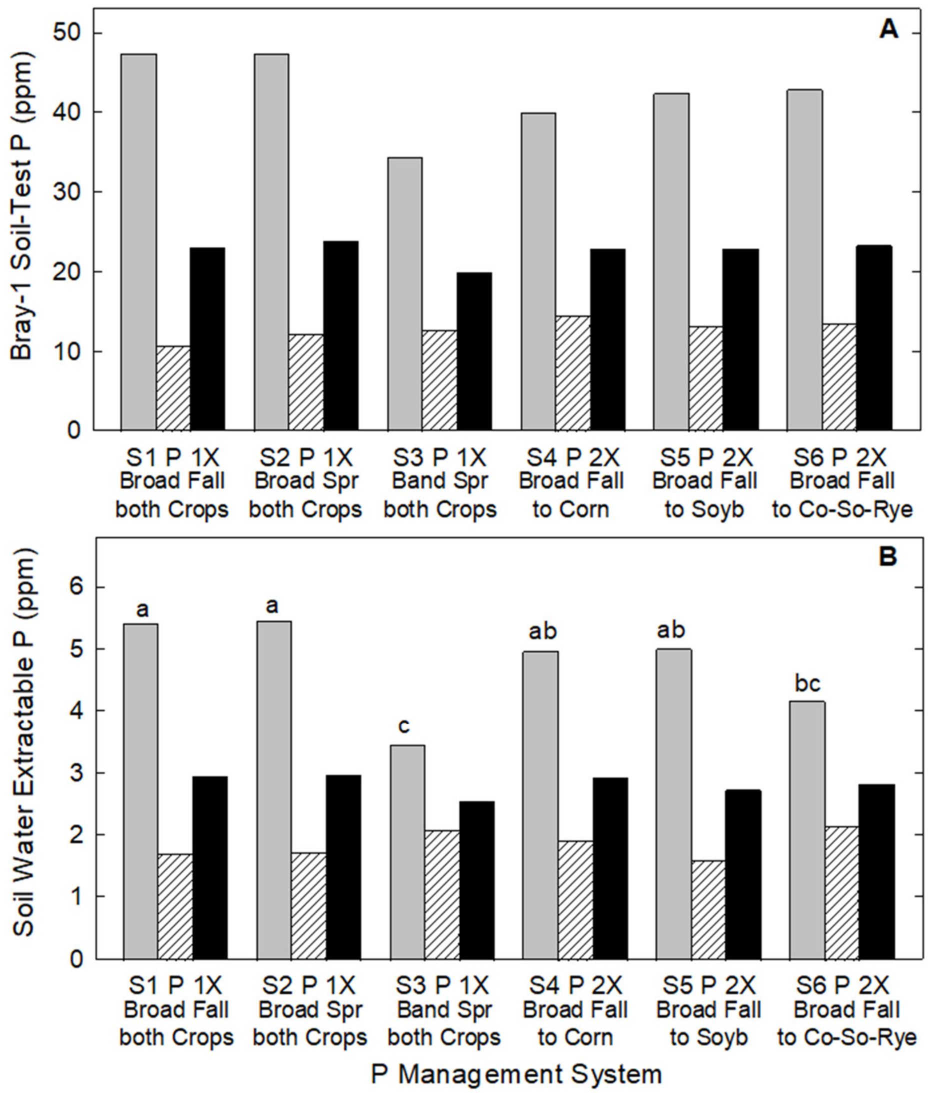

Fig. 2. Bray-1 (A) and water-extractable P (B) in fall 2019 for all systems (S1 to S6). 1X, annual rate of 50 lb P_2O_5/acre applied to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band); 2X, 100 lb P_2O_5/acre applied once every other year before corn, soybean, or either crop with a rye cover crop (Co-So-Rye). Different letters on top of the bars indicate statistical differences ($P \leq 0.10$) among means for the depth indicated.

Figure 2B shows that fall 2019 there were statistically significant differences for WEP soil P levels only in the 5-cm depth. The largest differences, and potentially important for water quality, are that WEP in the 5-cm depth was the lowest for System 3 (annual P rate banded), intermediate for System 6 (2X P application and managed with a cereal rye cover crop), and higher for the other systems. Although statistically WEP levels did not differ for the 5-15 cm depth, levels were the largest for System 3 (annual P rate banded) and System 6 (2X P application and managed with a cereal rye cover crop). Lower levels in the topsoil layer but higher in the 5-15 cm layer for System 3 can be explained by the planter-band P placement. Lower WEP levels for System 6 (cereal rye cover crop) also were observed for the Fall 2018 soil sampling (Fig. 1B). It is remarkable that higher WEP values in the 5-15 cm depth for these two systems was not observed for Bray-1 (Fig. 2A) or the Mehlich-3 and Olsen routine tests (not shown). A possible explanation for this difference between the soil P tests is more water-soluble P leaching from the surface layer to the 5-15 cm layer than leaching of the less water-soluble P forms measured by the routine tests.

Figure 3 shows results for the Bray-1 and WEP in soil samples collected between crop harvest and the P treatment applications in fall 2020. By the fall 2020 sampling time, all systems had received the same amount of P applied annually (1X) or twice the annual amount every two years (2X). The clear effects of band P placement and rye cover crop observed in fall 2019 were less obvious this fall for any test.

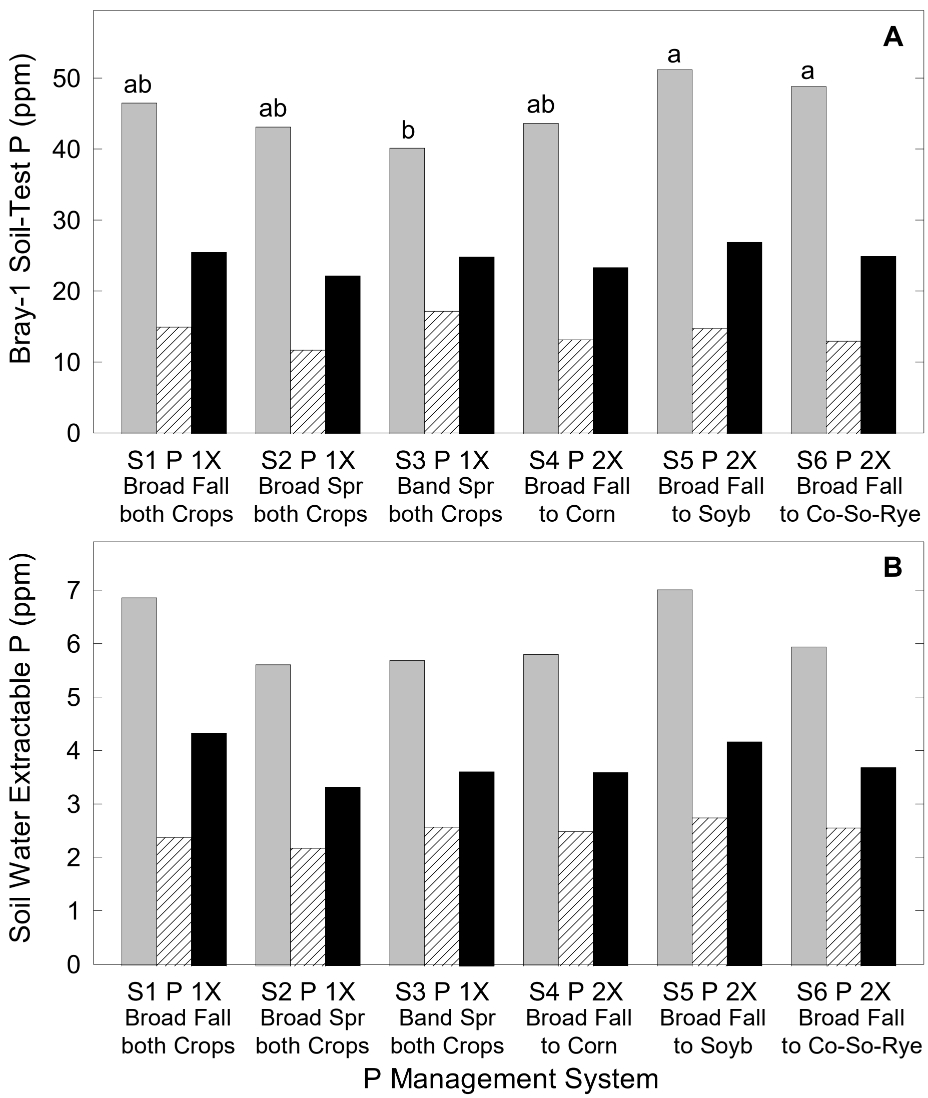

Fig. 3. Bray-1 (A) and water-extractable P (B) in fall 2020 for six systems (S1 to S6). 1X, annual rate of 50 lb P_2O_5/acre applied to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band); 2X, 100 lb P_2O_5/acre applied once every other year before corn, soybean, or either crop with a rye cover crop (Co-So-Rye). Different letters on top of the bars indicate statistical differences ($P \leq 0.10$) among means for the test and depth indicated.

In fall 2020 there were statistically significant differences among systems only for the Bray-1 test at the 5-cm depth. The highest observed Bray-1 (Fig. 3A) and WEP (Fig. 3B) values in the 5-cm depth were for System 1 (1X P broadcast in the fall) and System 5 (2X P broadcast before soybean). The highest values for both tests in the 5-15 cm depth were for System 3 (1X P banded with the planter).

The broadcast and subsurface banding P placement methods had a large impact on soil-test P stratification within the top 15 cm of soil. One average across the three years and all systems with broadcast fertilization, Bray-1 was 44.1, 14.6, and 24.4 ppm at depths 0-5, 5-15, and 0-15 cm, respectively, and WEP was 5.0, 1.9, and 3.0 ppm, respectively. Therefore, with broadcast P the Bray-1 and WEP P levels in the top 5-cm of soil were 3.1 and 2.7 times higher than concentrations in the 5-15 cm subsurface layer. The soil P stratification was lower for System 3 which had the band placement method, and the Bray-1 and WEP levels in the top 5-cm soil layer were 2.5 and 1.9 times higher than in the 5-15 cm layer. Since all systems were managed with no-tillage, stratification differences could impact on P loss with runoff.

Precipitation During the Study

Precipitation at this NW Iowa research site was about normal in 2019 but there was drought in 2020 and 2021 (Table 1). In 2019, the total annual rainfall for the period most relevant for cropping in Iowa (from October of one year to the end of September of the next year) was 824 mm, whereas the 20-year long-term average (1999-2018) for this period for the Cherokee weather station was 898 mm (the nearest with reliable long-term data to the NW research farm).

In 2020 the total precipitation of 651 mm, although lower than for 2019 or the 20-year averages, is misleading because there was about normal rainfall from July 1 until late September but very deficient rainfall before planting the crops until the end of June. In 2021 the total precipitation was lower (577 mm) than in 2020 but rainfall was almost normal before planting the crops, very low from the middle of March until late April, only slightly lower than normal during May and June, and very low again from July through late September. These amounts and patterns of rainfall will be important to consider when interpreting crop yield and runoff volume or P losses.

Table 1. Precipitation at the research site in three crop years and relevant periods.

Crop Year	Oct 1-Sep 30†	Oct 1-Mar 15	Mar 16-Apr 30	May 1-Jun 30	Jul 1-Sep 30
	-----------	-----------	mm	-----------	-----------
2019	824	227	106	217	274
2020	651	141	90	127	292
2021	577	218	69	197	93

† October 1 of one year to September 30 of the next year.

Crop Grain Yield and Phosphorus Removal with Grain Harvest

Corn and soybean grain yields for the three years are shown in Table 2. The yield levels were about normal for this NW Iowa location in 2019 but much lower in 2020 due to severe drought (Table 1) and only slightly lower than normal in 2021. On average across systems, grain yields in 2019, 2020, and 2021 were 219, 130, and 201 bu/acre for corn, respectively, and 61.2, 49.3, and 62.3 bu/ac re for soybean, respectively. There were no statistically significant grain yield differences among the systems for any crop in 2019 and 2020 (Table 2). In 2019, however, soybean yield for System 1 (fall annual P application to each crop) was 3 bu/acre lower than for the other systems. No grain yield differences among the systems evaluated was expected because the P management systems were designed to maintain soil-test P the between the Optimum and High interpretation categories. The very small yield difference for soybean in 2019 cannot be explained satisfactorily because in fall 2018 soil-test P at the top 15-cm depth for this system was in the middle of the High interpretation category (Fig. 1), for which no response to P is expected. Moreover, soil-test P was not the lowest among the systems. Therefore, we believe this small yield difference resulted from random variability.

Table 2. Corn and soybean grain yield in 2019, 2020 and 2021.

	2019		2020		2021	
Management system †	Corn	Soybean	Corn	Soybean	Corn	Soybean
	------------------------ Grain Yield (bu/acre) ‡ ----------------------					
1- Broadcast fall 1X P to both crops	218	59.1	130	45.7a	207	62.4
2- Broadcast spring 1X P to both crops	219	61.3	120	49.9b	203	60.5
3- Planter-band 1X P to both crops	219	63.1	124	50.7b	197	60.8
4- Broadcast fall 2X P to corn	na§	63.1	141	na	na	64.0
5- Broadcast fall 2X P to soybean	220	na	na	49.9b	199	Na
6- Broadcast fall 2X P to corn, cover crop	na	62.4	135	na	na	64.0

† 1X P, annual P maintenance rate; 2X P, twice the annual amount only every other year.
‡ Different letters by numbers within each column indicate statistical differences at $P \leq 0.05$.
§ na, treatment not applicable for this crop and year.

The amount of P removed with crop grain harvest (Table 3) tended to follow the yield levels because the grain P concentration variation due to P treatments or environmental conditions was relatively much smaller. Apparent differences among systems in some years did not attain statistical significance. The P removed on average across years and systems was 52.5 lb P_2O_5/acre for corn and 39.8 lb P_2O_5/acre for soybean.

Table 3. Phosphorus removed with crop grain harvest in 2019, 2020 and 2021.

	2019		2020		2021	
Management system †	Corn	Soybean	Corn	Soybean	Corn	Soybean
	----------------- Phosphorus removed (lb P_2O_5/acre) ----------------					
1- Broadcast fall 1X P to both crops	61.9	40.8	39.1	32.6	59.6	42.7
2- Broadcast spring 1X P to both crops	63.0	41.5	39.5	35.5	58.0	40.7
3- Planter-band 1X P to both crops	59.2	41.9	39.2	34.7	55.9	40.7
4- Broadcast fall 2X P to corn	na‡	42.2	44.8	na	na	na
5- Broadcast fall 2X P to soybean	62.8	na	na	35.3	57.8	44.3
6- Broadcast fall 2X P to corn, cover crop	na	41.3	42.0	na	na	43.1

† 1X P, annual P maintenance rate; 2X P, twice the annual amount only every other year.
‡ na, treatment not applicable for this crop and year.

The cereal rye cover crop dry matter yield (not shown) during the three years of the study was below normal for this research farm due to drier and colder than usual fall seasons. Overseeded rye had poor germination and it was not drilled in the spring expecting good tillering and to avoid soil disturbance. Aboveground biomass dry matter yield was 239, 87, and 61 lb/acre in 2019, 2020, and 2021, respectively. Therefore, the P uptake by the rye and recycling to the soil at the rye termination time in the spring also was very low, and was only 2.2, 0.78, and 0.46 lb P_2O_5/acre for 2019, 2020, and 2021, respectively.

Surface Runoff Results

Runoff events, flow, and soil loss

Precipitation at this NW Iowa research site was about normal in 2019 (Table 1). There was no measurable runoff from most plots since the time the first fall P treatments were applied in October 2018 until March 25, when there was runoff from all plots due to a mix of snowmelt and rainfall. The only additional runoff event occurred in October, when there was measurable runoff from only ten plots due to rainfall. In 2020, a drier year (Table 1) there was an event from all plots on March 31 due to a mix of snowmelt and rainfall, and an additional event in June with measurable runoff from 14 plots that occurred during three not contiguous days. In 2021, a year with slightly less than normal rainfall during the growing season (Table 1), there was snowmelt runoff event with runoff from all plots on March 8, an additional runoff event with runoff from all plots due to rainfall in August that occurred during two separate days, and another runoff event from 18 plots due to rainfall on October 1.

The runoff volume and soil losses were lower than would be expected for fields of the region with similar slope because the site was managed with no-tillage since 2018. Contrary to expectations given that total rainfall was about normal in 2019 but very low in 2020 and 2021 (Table 1), Fig. 4 shows that runoff volume in 2019 was very low and significantly lower than in 2020 and 2021. This happened because rainfall was low during April and June (Table 1) when intense rainfall and runoff normally are more likely and also because the rainfall was distributed in several low-intensity events (not shown). In 2019 there were statistically significant differences in runoff but were very small and of little relevance due to the very low overall runoff. In 2020 and 2021 there was greater runoff, but there were no statistically significant differences in any year. The variation was larger in 2020 with apparently greater runoff amounts for Systems 5 and 6.

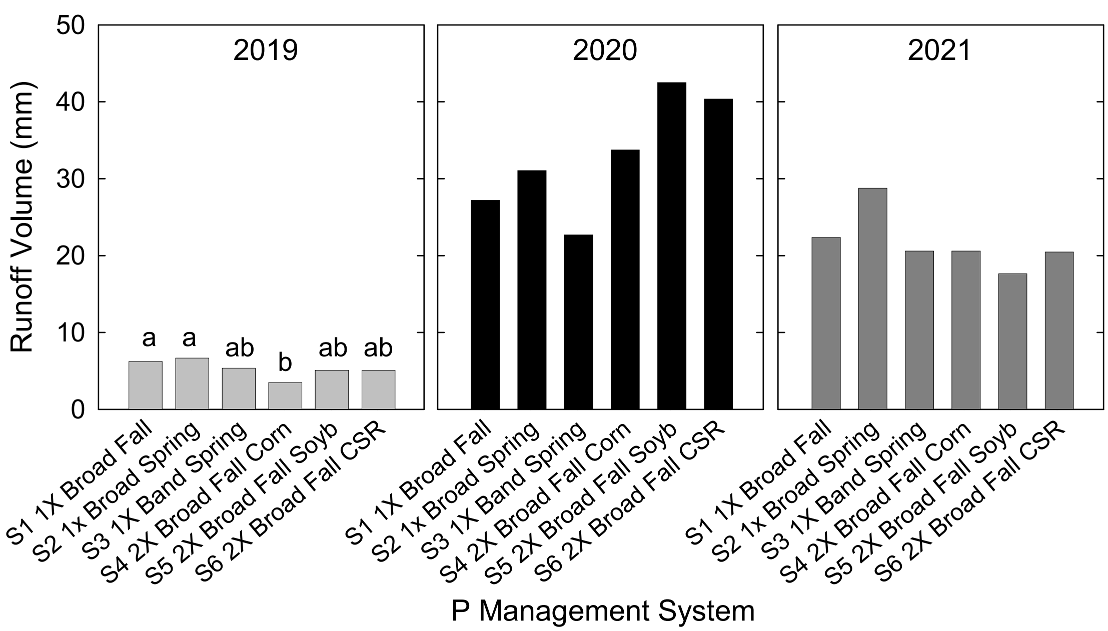

Fig. 4. Runoff for the three years of the study for six P management systems (S1 to S6). 1X, annual rate of 50 lb P_2O_5/acre applied to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band); 2X, 100 lb P_2O_5/acre applied once every other year before corn, soybean, or either crop with a rye cover crop (CSR). Different letters on top of the bars indicate statistical differences ($P \leq 0.10$) among systems.

Figure 5 shows that soil losses were very low in the three years of the study (less the 350 kg per ha) and the variation observed seldom could be reasonably related to the management system, crop, or runoff. The variation across systems was smaller in 2019 than in 2020 or 22021, but the apparent differences were not statistically significant. In 2020 soil losses were by far the lowest for System 3 (planter banded P). which also had the lowest runoff (Fig. 4). Soil loss for the System 6 (with a cereal rye cover crop) were not the lowest probably because runoff was among the greatest (Fig. 4). In 2021 there was large soil loss variation across systems but the variation did not match the observed runoff variation (Fig. 4).

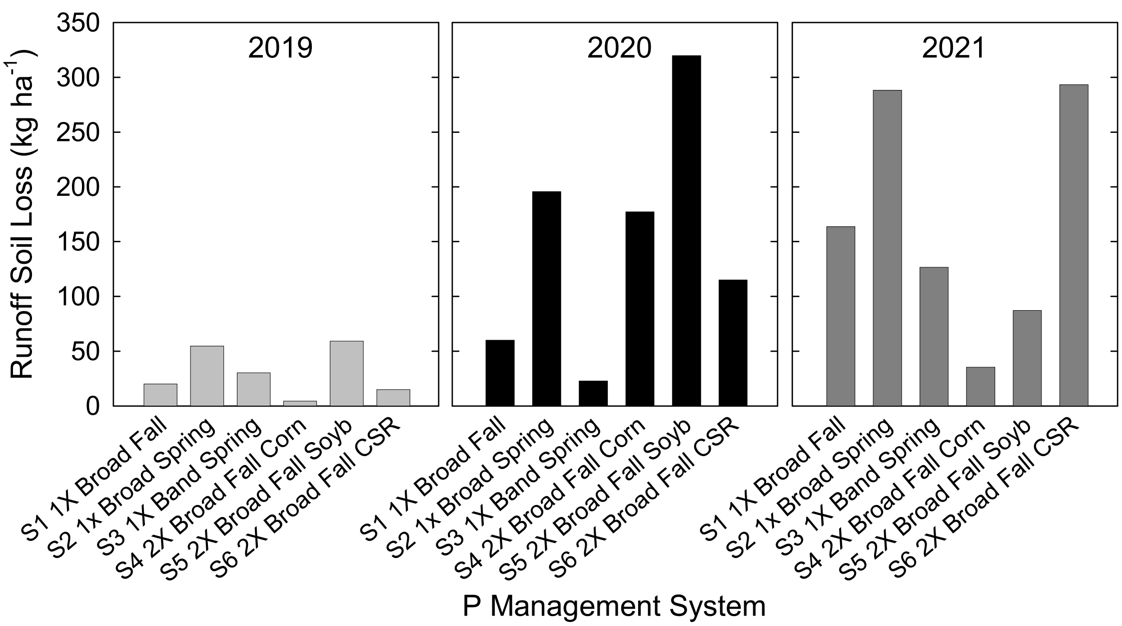

Fig. 5. Runoff during the three years of the study for six P management systems (S1 to S6). 1X, annual rate of 50 lb P_2O_5/acre applied to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band); 2X, 100 lb P_2O_5/acre applied once every other year before corn, soybean, or either crop with a rye cover crop (CSR).

Use of a cereal rye cover crop had no clear effects on runoff and soil losses, probably because the no-till management and less biomass production due to adverse fall growing conditions in the three years of the study. Ongoing Iowa research is showing proportionally much less runoff and soil loss reduction from using cover crops with no-till than with tillage in corn-soybean rotations (Gomez-Botero, et al., 2020; Mallarino et al., 2021b).

Runoff P Concentrations

Figure 6 shows the average concentrations in runoff of total P and the fractions bioavailable P (BAP), total dissolved P (TDP), and dissolved reactive P (DRP) for each P management system evaluated in the study for each year and the average across years. As expected, the concentration of the BAP fraction of the total P was slightly larger or similar to the TDP concentration and these two were larger than the DRP concentration. The particulate P fraction (sediment-bound P) was small in all years and for all systems, which can be explained by the no-till management and low soil loss.

In 2019, apparent differences among systems did not reach statistical significance, which is reasonable because soil Bray-1 P and water extractable P in fall 2018 did not differ among the systems (Fig. 1). However, it is difficult to relate soil-test P levels with runoff P concentrations since runoff P concentrations always are much more affected by fresh application of P fertilizer than by any soil-test P differences before the application.

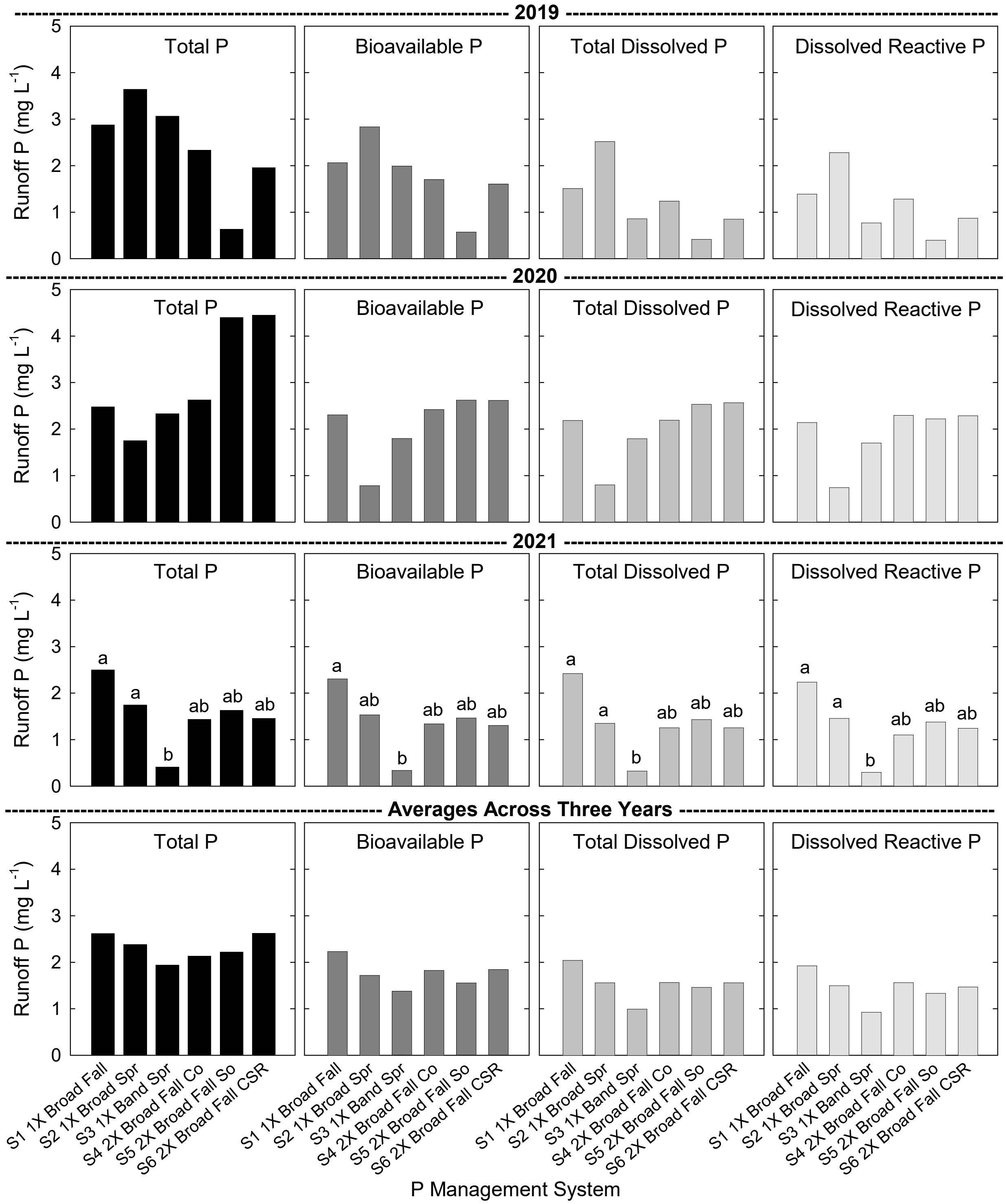

Fig. 6. Concentrations in runoff of several P fractions for the three years of the study for six P management systems (S1 to S6). 1X, annual rate of 50 lb P_2O_5/acre applied to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band); 2X, 100 lb P_2O_5/acre applied once every other year before corn, soybean, or either crop with a rye cover crop (CSR). Different letters on top of the bars indicate statistical differences ($P \leq 0.10$) among systems.

Runoff P concentrations tended to be higher for Systems 1, 2, and 3 (with annual P applications) than for the other systems because the annual P rates were applied in late fall 2018 or spring 2019 but no 2X P rate was applied because had been applied in fall 2017.

In 2020, apparent runoff P concentration differences among the systems did not reach statistical significance. Obvious higher total P concentrations for Systems 5 and 6 make sense because the 2-year P rate was applied late in fall 2019, but lower total P concentration for System 4 is puzzling because the 2-year P rate also was applied for this system. The only obvious (but not statistically significant) difference for BAP, TDP and DRP runoff P fractions were very low concentrations for System 2 (1X P rate broadcast in the spring), which cannot be explained since losses for System 3 were higher and the same 1X P rate was banded in the spring.

In 2021 most runoff P concentrations were lower than in the previous two years and there were statistically significant differences among the systems. Concentrations of all P fractions were the lowest for System 3 (annual P rate banded in the spring), the highest for Systems 1 and 2 (annual P rate broadcast in the fall or spring) except only for TDP for System 2, and intermediate for the three systems with 2X P application every other year (Systems 4, 5, and 6). It is important to consider that only the annual P rates were applied for the 2021 crop year (Systems 1, 2, and 3) but no 2X P rate was applied to Systems 4, 5, and 6 because it had been applied in fall 2019. Therefore, higher runoff P concentrations for Systems 1 and 2 compared with Systems 4, 5, and 6 (all three with fall application) could be explained by recent P applications for Systems 1 and 2 (although of the lower P rate) but none for Systems 4, 5, and 6 since fall 2019.

On average across the three years there were no statistically significant differences, which can be explained by sometimes opposite results for each year. However, one result is of potential water quality relevance. The concentrations of all runoff P fractions were the lowest for System 3, which is reasonable because this system involved subsurface P banding of the annual P rate. Other apparent differences among systems were very small and some do not have reasonable explanation.

Runoff P losses

The impacts on water quality of runoff P concentrations is mediated by the runoff volume, which determines the actual amounts and forms of P that will reach water bodies. The losses of all runoff P fractions were very low in the three years of the study because of the no-till management.

Figure 7 shows the P losses for the three years and the average across years. In 2019 the runoff P losses were the lowest of all years because of low runoff (Fig. 1) even with almost normal rainfall (Table 1) mainly due to a rainfall distribution in numerous low-intensity events. There were statistically significant differences among systems only for the DRP and TDP dissolved P fractions. The P losses were the highest for System 1 (annual P rate broadcast in the fall), intermediate for System 2 (annual P rate broadcast in the spring), and the lowest for the other systems. The BAP and total P losses also tended to be higher for Systems 1, 2, and 3. These system differences are explained by application of the annual P treatments for this crop year but no application for Systems 4, 5, and 6 (twice the annual P rate broadcast every other year in the fall) because had been applied in fall 2017 for the 2018 and 2019 crop years. But all differences were very small due the overall low runoff.

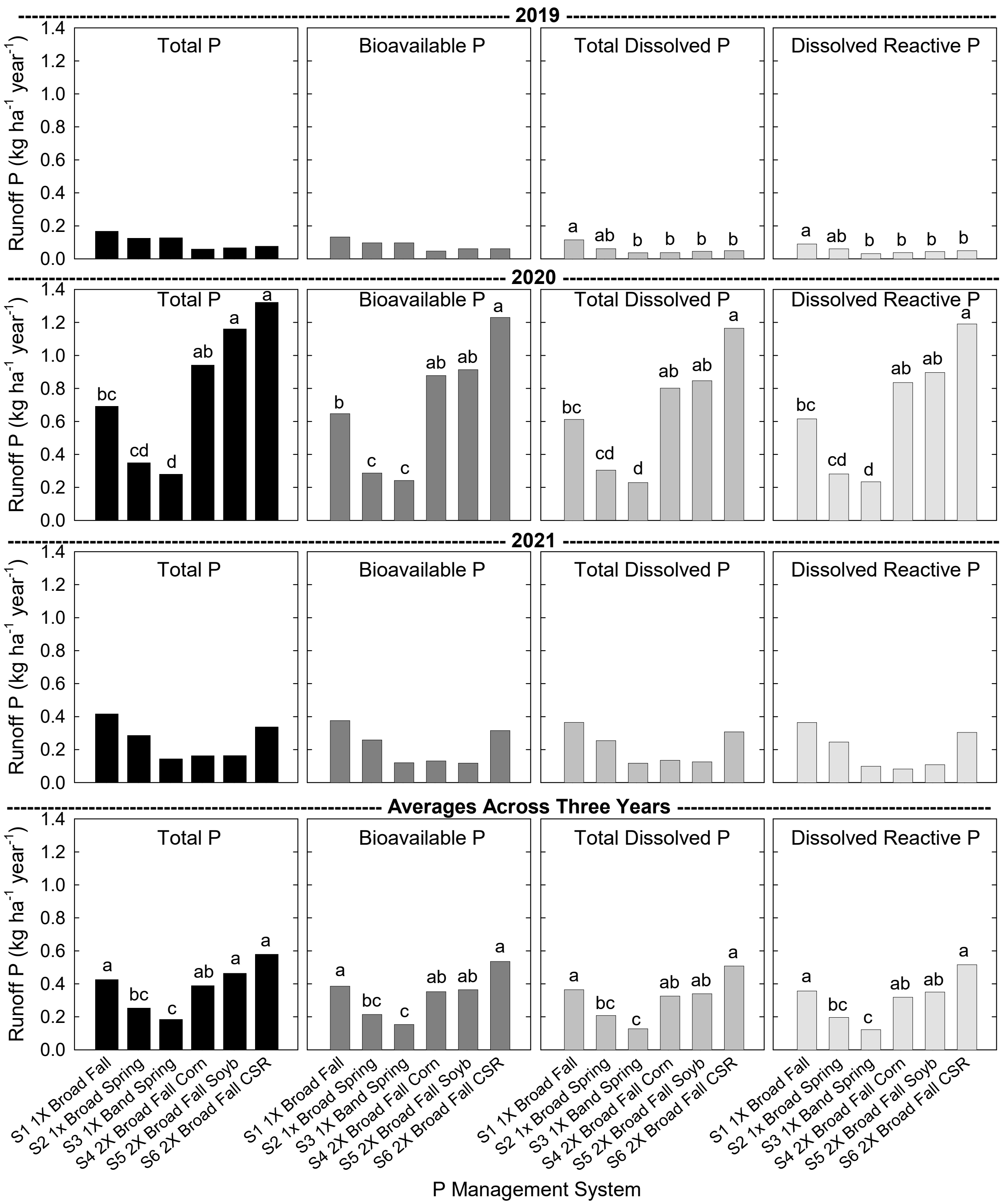

Fig. 7. Losses with runoff of several P fractions for the three years of the study for six P management systems (S1 to S6). 1X, annual rate of 50 lb P_2O_5/acre applied to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band); 2X, 100 lb P_2O_5/acre applied once every other year before corn, soybean, or either crop with a rye cover crop (CSR). Different letters on top of the bars indicate statistical differences ($P \leq 0.10$) among systems.

In 2020 losses of all runoff P fractions were higher for Systems 4, 5, and 6. This result is reasonable because all P treatments were applied for this crop in fall 2019 or spring 2020, including the fall-applied

2X P rates for Systems 4, 5, and 6. A remarkable result was that P losses were the lowest for Systems 2 and 3, which received the annual 1X P rate either broadcast or banded in the spring, and were intermediate for System 1, which received the 1X P rate broadcast in the fall. For the 2021 crop, all systems had received the same P rate across the previous two years, and there were no statistical differences among the systems.

On average across the three years the P losses for all P fractions showed about the same differences observed each year, and there were statistically significant differences. Losses were the lowest for Systems 2 and 3, which received the 1X P rate broadcast or banded in the spring. Losses were higher for the other systems, including System 1 which involved broadcasting the annual rate in the fall and the systems which involved broadcasting twice the annual rate every other year only before corn (System 4), soybean (System 5), or either crop managed with a cover crop (System 6). Losses for Systems 1 and 6 seemed slightly higher than for Systems 4 and 5 but the statistical confirmation of this difference was weak. It is important to note that lower runoff P loss for Systems 2 and 3 compared with System 1 may have resulted from the timing of the runoff for these three years. Contrary to what is most common in Iowa, most runoff occurred in March, before the spring P treatments were applied. Usually, large runoff amounts occur from April to late June when high-intensity rainfall is common.

Broadcasting the annual P rate or twice its amount every other year with no-tillage did not result in consistently different P losses (Fig. 7). Previous Iowa research showed inconsistent P rate effects on runoff P loss with P applied in the fall. A study conducted under natural rainfall for 6 years showed no consistent differences between annual P application of 50 lb P_2O_5/acre or a 100-lb rate applied every other year (Mallarino et al., 2019) but other studies showed more runoff P when a 100-lb rate was applied (Mallarino et al., 2021a, 2021b). Many Iowa rainfall simulation studies showed that even a short 2-week delay of runoff after broadcasting 100 lb P_2O_5/acre with fertilizer or manure without incorporation into the soil sharply decreases dissolved and total P losses with runoff compared with runoff occurring within 48 hours of the application (Allen and Mallarino, 2008; Kaiser et al., 2009, Mallarino and Haq, 2015).

As was observed for runoff and soil losses, use of a cereal rye cover crop in this study had no clear effects on runoff P loss, probably because of the no-till management and less biomass production than normal due to adverse fall growing condition. Recently completed 6-year Iowa research showed proportionally less dissolved and particulate P loss from using cover crops with no-till than with tillage in corn-soybean rotations (Gomez-Botero, et al., 2020; Mallarino et al., 2021b).

Figure 8 shows the proportion of DRP, TDP, and BAP losses expressed as the percentage of the total runoff P. As was observed for runoff P concentrations, most of the total runoff P loss was comprised of dissolved or bioavailable P forms. On average across all systems, DRP, TDP, and BAP losses were 71, 74, and 85% of the total P loss. Approximately similar proportions were observed with no-till management by previous Iowa research (Mallarino et al., 2019). These proportions of the runoff P fractions differed across systems only for both dissolved P fractions DRP and TDP.

The most important result confirmed by statistics in Fig. 8 is that the proportion of DRP and TDP in runoff were the lowest for System 3, which was managed with subsurface P banding. These results may be explained by less soluble P at or near the soil surface with subsurface banding, which reduces relatively more the loss of dissolved P forms compared with BAP or particulate P. This explanation is supported by less stratification (less P in the surface soil layer than in the subsurface layer) for Bray-1 routine test and the water-extractable soil P test with banding (Figs. 1, 2, and 3).

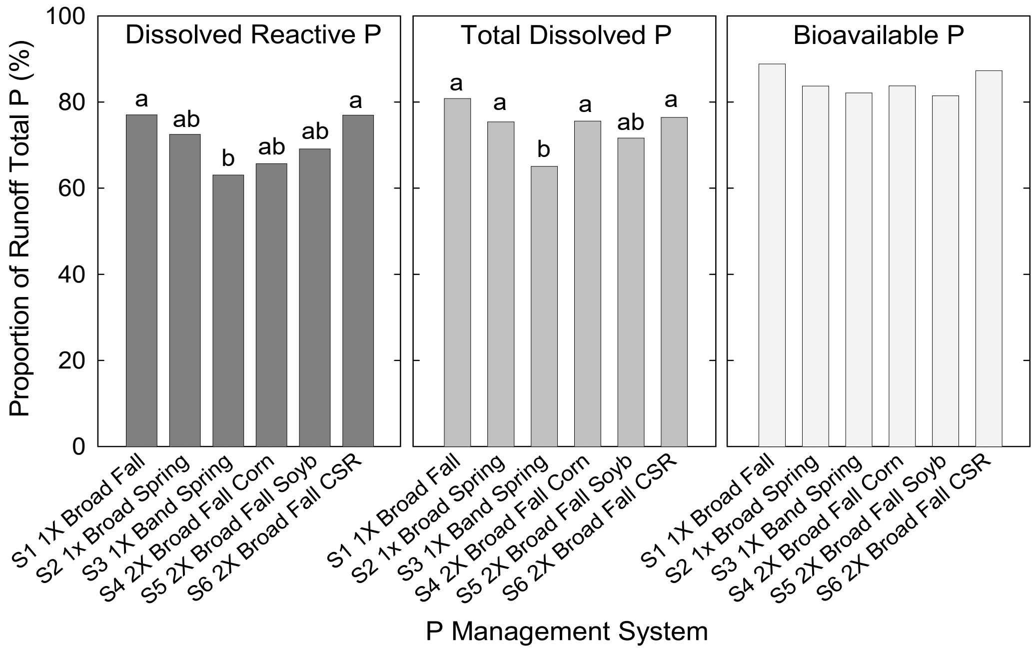

Fig. 8. Dissolved and bioavailable P proportions of the total runoff P loss for six systems (S1 to S6) on average across three years. 1X, annual rate of 50 lb P_2O_5/acre applied to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band); 2X, 100 lb P_2O_5/acre applied once every other year before corn, soybean, or either crop with a rye cover crop (CSR). Different letters on top of the bars indicate statistical differences ($P \leq 0.10$).

Crop effects on runoff P losses

The previous sections did not specifically address potential crop effects on runoff P loss and results for Systems 1, 2 and 3 (which received the 1X annual P rates) were averages across the two crops present each year on adjacent plots. These systems can be used to compare crop effects because each crop was treated similarly each year. This comparison cannot be done for the other systems because of the differential P treatments and because were not present every year. It must be remembered that corn was planted on plots with soybean residue and soybean was planted on plots with corn residue, and that all plots were managed with no-tillage.

Figure 9 shows the average runoff volume and soil loss across three years for each crop of Systems 1, 2, and 3. The runoff differed among crops only for System 2, for which was greater for soybean (planted on corn residue) than for corn (planted on soybean residue). Figure 9 also shows that the soil loss differed between crops only for System 1, being greater for corn (planted on soybean residue). As was mentioned before, most runoff in the three years of the study occurred in March, when soil was covered by corn or soybean residue, and little runoff occurred after planting and when there was significant crop canopy.

The results in Fig. 9 indicate that for one system (System 2) runoff was greater from soybean (planted on corn residue) and the crops did not differ for the other systems, but soil loss was greater from corn (planted on soybean residue) for System 1 and the crops did not differ for the other systems. Two previous 6-year studies in NW Iowa (Mallarino et al. 2013; Mallarino et al. 2019) showed no consistent runoff differences from corn or soybean plots managed with no-tillage but soil loss tended to be higher from corn (planted on soybean residue). Our study was conducted only for three years and most with less rainfall than normal, so strong conclusions about crop effects on runoff and soil losses are risky.

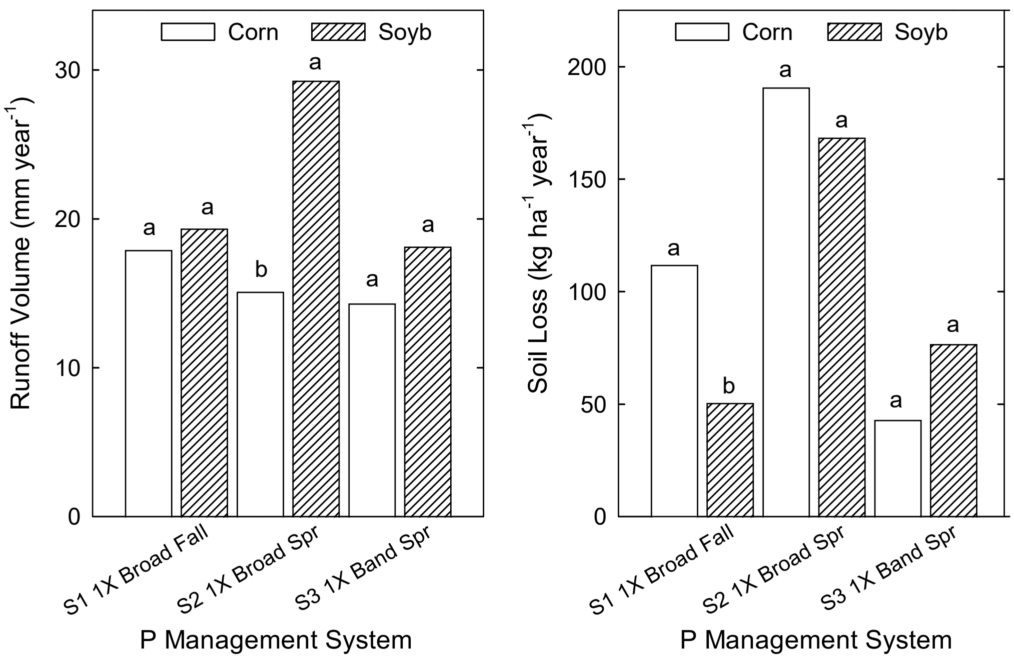

Fig. 9. Runoff and soil loss averages across three years as affected by the crop for the three systems (S1, S2, and S3) with 50 lb P_2O_5/acre/year to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band). Different letters on top of the bars indicate statistical differences ($P \leq 0.10$) between crops for each system.

Figure 10 shows the average P losses across three years for each crop of Systems 1, 2, and 3; all receiving the 1X annual P rate.

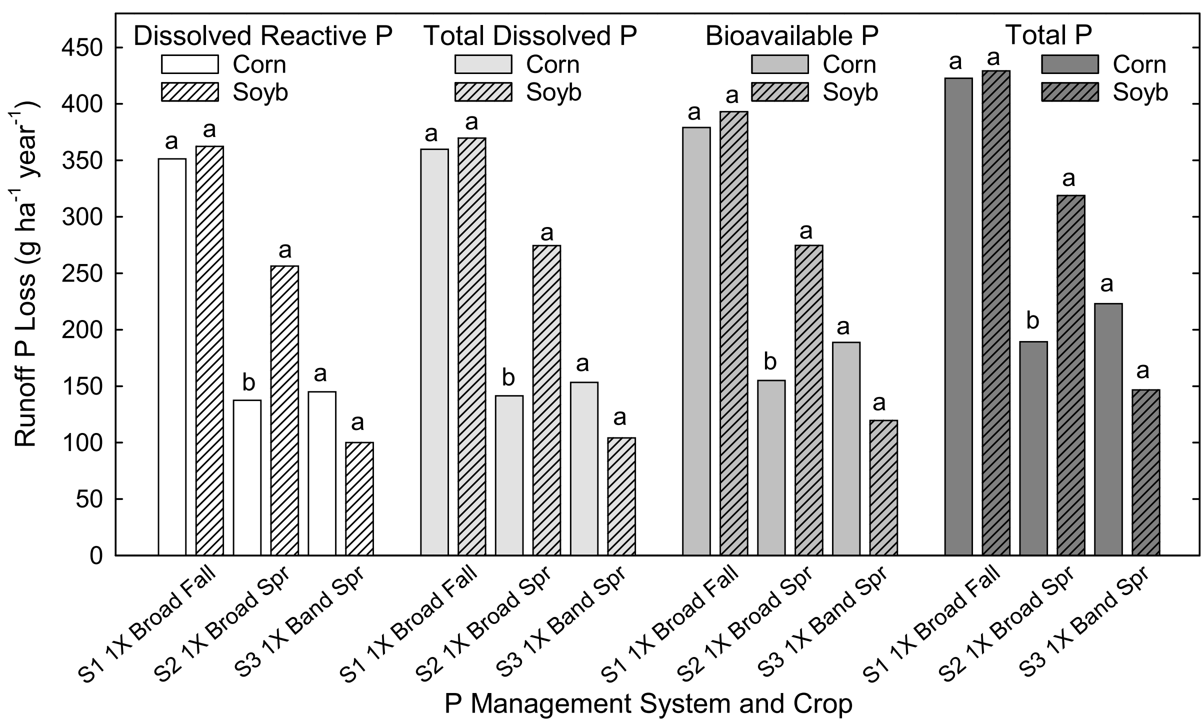

Fig. 10. Runoff P loss means across three years as affected by the crop for the three systems (S1, S2, and S3) with an annual rate of 50 lb P_2O_5/acre/year to each crop broadcast in the fall or spring (Broad) or banded with the planter (Band). Different letters on top of the bars indicate statistical differences ($P \leq 0.10$) between crops for each system.

The losses of all runoff P fractions for System 1, which received broadcast P in the fall, were similar for both crops. For System 2, which received broadcast P in the spring, the P losses were greater with soybean than with corn but for System 3, which received banded P in the spring, the P losses were slightly greater with corn than with soybean. Runoff volume in Fig. 9 showed much more runoff for System 2 with soybean (planted on corn residue) than with corn (planted on soybean residue), which could explain the P losses for this system. However, we cannot explain satisfactorily the higher runoff for this system and crop because all management practices were similar for the three systems and both crops.

SUMMARY AND CONCLUSIONS

This study was conducted during three years at a northwest Iowa site to evaluate the impacts of broadcast and subsurface banding of P fertilizer and the timing of broadcast P application on total, bioavailable, and dissolved P loss with surface runoff in corn-soybean rotations managed with no-tillage. In addition to the runoff measurements, the study included evaluating P management system effects on crop grain yield, P uptake and recycling by a cover crop, and soil-test P measured by various procedures. The results for each measurement are summarized by the following points.

Phosphorus source and application

- Triple superphosphate (0-46-0) was the P source for all systems evaluated.
- The objective of the P fertilization was to maintain soil-test P between the Optimum and High Iowa interpretation categories by applying a maintenance rate annually or twice this amount every two years.
- A P rate of 50 lb P_2O_5/acre was applied annually for System 1 (broadcast in the fall), System 2 (broadcast in the spring), and System 3 (banded with the planter) whereas a 100-lb rate was broadcast in the fall every two years for System 4 (only before corn), System 5 (only before soybean), and System 6 (only before corn with a cereal rye cover crop for both crops).

Soil-test P

- As is often the case with no-till management, there was large soil P stratification within the top 15 cm of soil and the P placement method had a large impact on the stratification.
- On average across all years and systems with broadcast fertilization, Bray-1 was 44.1, 14.6, and 24.4 ppm at depths 0-5, 5-15, and 0-15 cm, respectively, and WEP was 5.0, 1.9, and 3.0 ppm, respectively, and P in the top 5-cm of soil was 3.1 and 2.7 times higher than the concentrations in the 5-15 cm subsurface layer.
- The band placement method reduced the P stratification, and the Bray-1 and WEP levels in the top 5-cm soil layer were only 2.5 and 1.9 times higher than in the 5-15 cm subsurface layer.

Grain crop P removal and cover crop P recycling

- The P removed with corn and soybean grain harvest did not differ across systems and on average was 52.5 lb P_2O_5/acre for corn and 39.8 lb P_2O_5/acre for soybean.
- The cereal rye cover crop yield during the three years of the study was below normal due to drier and colder than usual fall seasons and was 239, 87, and 61 lb/acre in 2019, 2020, and 2021, respectively. Therefore, the aboveground rye P uptake and recycling to the soil at the termination time in the spring was only 2.2, 0.78, and 0.46 lb P_2O_5/acre for 2019, 2020, and 2021, respectively.

Runoff volume and soil loss

- The runoff volume and soil losses were lower than would be expected for fields of the region with similar slope because the site was managed with no-tillage since 2018. Contrary to expectations given a total rainfall amount that was about normal in 2019 but very low in 2020 and 2021, runoff was much lower in 2019 than in 2020 and 2021.

- Although in Iowa runoff usually is higher from April to late June, when high-intensity rainfall is common, in the three years of the study most of the runoff occurred in March, after fall P treatments application but before the spring P treatments were applied, this is important to consider when interpreting results of runoff P loss for fall and spring P treatments.

- Soil losses were very low in the three years of the study (less the 350 kg per ha) and the variation observed could not be reasonably related to the management system, crop, or runoff volume.
- Use of a cereal rye cover crop had no effects on runoff and soil losses probably because of the no-till management and less biomass yield due to adverse fall growing conditions in the three years of the study.

Runoff P loss
- The losses of all runoff P fractions were very low in the three years of the study because of the no-till management. Runoff P losses were especially very low in 2019 because of low runoff.

- On average across the three years, the losses for all P fractions with runoff showed about the same differences. Losses were the lowest for Systems 2 and 3, which received the annual P rate broadcast or banded in the spring. Losses were higher for the other systems with no strong statistical support for observed differences. Lower runoff P loss for Systems 2 and 3 compared with Systems 1, 4, 5, and 6 may have resulted from the timing of the runoff for these three years.
- Contrary to what is most common in Iowa, most runoff occurred in March when the fall systems had been applied but before the spring P treatments were applied. In Iowa, normally most runoff occurs from April to late June when high-intensity rainfall is more common.

- Subsurface P banding reduced dissolved runoff P loss more than bioavailable and particulate P losses. This was explained by P stratification with banding (proportionally lower P concentration in the topsoil than in subsurface soil).

- The proportion of dissolved reactive P, total dissolved P, and bioavailable P of the total P one average was 71, 74, and 85%, respectively. The bioavailable P proportion of the total P loss was not affected by the systems. The proportions of both dissolved P fractions were the lowest for the system with subsurface P banding (63 and 65%, respectively), compared with the average across the other systems (72 and 76%, respectively).

- Broadcasting the annual P rate or twice its amount every other year did not result in consistent differences for dissolved or total P losses in this study.

- Use of a cereal rye cover crop had no clear effects on runoff and soil losses, probably because of the no-till management but also because less than normal biomass production due to adverse fall growing conditions in the three years of the study.

- Runoff volume, soil loss, and P loss were not clearly affected by the crop (corn or soybean) in the study, probably because no-till management tends to diminish usually larger losses observed from soybean residue managed with tillage.

In conclusion, the study showed that spring broadcast or subsurface P banding in the spring of the annual maintenance P rate for corn and soybean managed with no-tillage reduced dissolved and total P losses compared with a similar or larger P rates broadcast in the fall. However, this result was partially explained by runoff occurring mostly in March of every year when the fall broadcast applications had been done but before the P applications in the spring. In Iowa, most often most surface runoff occurs between April and late June, when high-intensity rainfall is more comment.

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