FINAL REPORT TO THE IOWA NUTRIENT RESEARCH CENTER
FOR THE PROJECT

Impacts of Cover Crops on Phosphorus and Nitrogen Loss with Surface Runoff

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INTRODUCTION

No-till management and cover crops are recognized nutrient management practices that are considered by the Iowa Nutrient Reduction Strategy and both state and federal agencies. Research in Iowa or the north-central region has demonstrated the effectiveness of no-till management at reducing soil-bound P loss from fields and that cover crops significantly reduce the amount of nitrate lost with subsurface drainage. However, the impacts of no-till management on N and dissolved P loss from corn and soybean fields and of cover crops at reducing loss of N or P with surface runoff have not been sufficiently studied. Therefore, the main objectives of a six-year study were to assess at a field scale and natural rainfall effects of no-till and cover crops (compared with tillage and no cover crop) for corn-soybean rotations at reducing soil, nitrogen (N) and phosphorus (P) loss with surface runoff in fields with high to very high soil-test P levels.

The field data collection was conducted from 2015 to 2020 with funding provided by Iowa Nutrient Research Center (INRC). The funding was provided in successive two-year grants, each with preliminary final reports to the INRC, until results from 2015 through 2018 were summarized in a report submitted to the INRC in 2019. Thereafter, two additional one-year grants allowed for continuing field data collection until the end of 2020 to complete six years of the corn-soybean rotation and for finishing laboratory analyses and data management during 2021. This final comprehensive report summarizes results for the six years of the study

PROJECT TIMELINE AND PROCEDURES

Work for the project began early in summer 2013 to locate an appropriate field for the study. By the fall of that year an appropriate 17-ha field was identified at the Iowa State University (ISU) Hermann Farm located in southern Boone County which had been managed for bulk production of corn and soybean with no-till management for about ten years. The dominant soil type was Clarion loam with very small areas of Nicollet loam and Webster clay loam (less than 0.2 ha each). A preliminary dense grid soil sampling in fall 2013 showed that soil-test P to a 15-cm depth ranged from the Optimum to Very High ISU soil-test P interpretation categories (Mallarino et al., 2013). Therefore, in early spring 2014, P fertilizer was applied using variable-rate technology to uniformize as much as possible soil-test P levels across the field.

The systems we wanted to evaluate were chisel-plow/disk tillage or no-tillage with or without a cereal rye cover crop. The four management systems with three replications were established on 12 small watersheds ranging from 0.61 to 1.25 ha in size delimited by existing terraces and newly constructed berms (Fig. 1). Slopes ranged from 1.51 to 3.11% and the systems were assigned to the three replications (blocks) according to slope. The tillage treatments (chisel/plow-disk and no-till) were first established in spring 2014, and soybean was planted following the previous rotation.

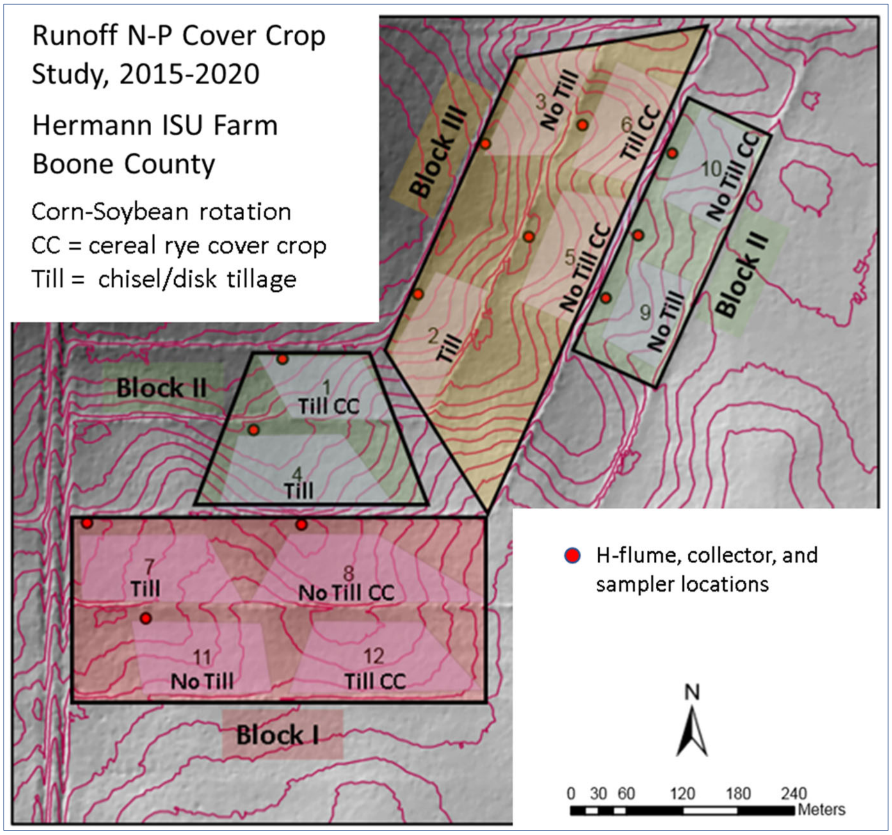

Figure 1. Field, watersheds, and experimental layout used for the study.

The cover crop treatments were initiated in fall 2014 by drilling the cereal rye after soybean harvest. The cereal rye cover crop (Elbon variety) was seeded each year at a rate of 168 kg/ha. For the first and second runoff collection years (2015 and 2016), the rye was seeded by drilling seeds in the fall immediately after harvesting the corn or soybean crops. For the last four years, the cereal rye was over-seeded in early September of each year before the crop physiological maturity and harvest. The rye was chemically terminated in April or early May depending on the year.

The tillage for the watersheds managed with tillage was done in the spring 7 to 10 days after the rye was terminated. The tillage for ground with cornstalks with or without the cover crop involved chisel-plowing or disking with a heavy disk harrow and use of a field cultivator to prepare the seedbed. Tillage for ground with soybean residue and the cover crop involved disking with a heavy disk harrow and field cultivation. Tillage for soybean ground without the cover crop involved only field cultivation. The planting date for all crops of the watersheds managed with no-till or tillage was planned for immediately after the tillage operations as allowed by soil conditions.

Soil samples from each watershed and from depths of 0-5 and 0-15 cm were collected every year before each crop was planted. For the 2015 crop, the soil samples were taken in the spring. Afterwards the samples were taken from the same two depths in the fall after harvest and before any new P fertilizer application. To maintain high-testing P levels, P fertilizer (triple superphosphate) was broadcast across all watersheds at a rate of 224 kg P/acre in fall 2016 and again in fall 2018. Samples were analyzed for soil P by methods supported by ISU for crop production and the Iowa P Index (Bray-1, Olsen, and Mehlich-3) all with the standard colorimetric determination of extracted P (see Table 1). The average soil pH across all years for the 15-cm depth was 6.27, 6.09, 6.10, and 6.26 for the systems tillage without the cover crop, tillage with the cover crop, no-till without the cover crop and no-till with the cover crop, respectively, and for the 5-cm depth was 6.53, 6.34, 6.29, and 6.43, respectively. The average soil organic matter across all years for the 15-cm depth was 2.50, 2.56, 2.79, and 2.79% for the systems tillage without the cover crop, tillage with the cover crop, no-till without the cover crop and no-till with the cover crop, respectively, and for the 5-cm depth was 2.84, 2.88, 3.21, and 3.09%, respectively.

Nitrogen rates as urea ammonium-nitrate liquid fertilizer for corn crop were 10 to 15 kg N/ha higher than the Maximum Return to N (MRTN) rate as suggested by the ISU Extension N Rate Calculator. The N rates varied from 165 to 175 kg N/ha across the years and were split into 60 kg N/ha banded with the planter besides and below the seeds with the rest sidedressed (injected) at the V4-V6 growth stage. Non-limiting but not excessive uniform rates of potassium, sulfur, and zinc were broadcast uniformly and periodically across all the watersheds.

Crop measurements were cereal rye cover crop aboveground dry matter yield and both N and P recycled at its termination in the spring, corn and soybean grain yield, and N and P removed with grain harvest. The rye biomass yield was estimated by cutting aboveground plant parts (2 cm from the ground) in several 930-cm^2 areas just before it was terminated in the spring. The biomass samples were dried and processed to measure dry matter yield and both total N and P concentrations to determine N and P accumulation and amounts recycled to the soil. Corn and soybean grain was harvested with a farm combine equipped with a calibrated yield monitor, a GPS receiver, and georeferencing using a ground-based RTK system. Yield data was imported into ArcGIS to use only data from the flow area of each watershed and were adjusted to 15 and 13% moisture for corn and soybean, respectively. Corn and soybean grain for total N and P analyses was sampled by hand immediately before harvest by picking corn ears or cutting soybean plants from 7.6-m sections of several rows across each watershed and was threshed with a small stationary thresher.

The equipment to receive and measure and sample runoff for each watershed was bought during 2014. The equipment included 0.46-m H-flumes to receive runoff and ISCO 6712 autosamplers with appropriate electronic hardware and software. The equipment installation was finished in March 2015 when soils thawed. Therefore, runoff collection began in spring 2015 before the first-year rye cover crop was terminated, the tillage systems had been in place for one year, and before corn was planted. The automatic runoff sampler was equipped with one liter 24 bottles programed to take a 300-ml sample to each bottle after every one-cubic meter of runoff (Fig. 2).

Figure 2. H-flumes and equipment used in the study to measure and sample runoff.

Runoff from each water shed was analyzed for total solids, total P, dissolved reactive P (DRP), total N, dissolved ammonium, and dissolved nitrate. Unfiltered runoff samples were used to measure total solids, Kjeldahl-digested N (organic N and ammonium by EPA-111-A Revision 5 and EPA-136-A Revision 4), and total P by the sodium-hypobromite method (Dick and Tabatabai, 1977; Cihacek and Lizotte, 1990) adapted to runoff. Subsamples of runoff were filtered through 0.45-um filters within 24 hours of the sample collection to measure the dissolved nutrient fractions ammonium (EPA-103-A Revision 10 method), dissolved nitrate (EPA-127-A Revision 7 method), and DRP by the standard Murphy and Riley colorimetric method.

Analyses of variance (ANOVAs) to assess differences among systems for all crop, cover crop, soil, and runoff measurements by year and across years were conducted as appropriate for a randomized complete-bock design (RCBD) using the GLIMMIX procedure of SAS. The by year ANOVAs assumed fixed treatment (four) and block (three replication) effects. The across years ANOVAs assumed a split-plot design with treatment as large plots and year as subplots. Differences among the treatment means were assessed by using the PDIFF and LINES options of the LSMEANS statement of GLIMMIX to output pairwise comparisons of means only when the treatments main effect was significant at $P \leq 0.10$. For the runoff measurements we conducted similar ANOVAs on log-transformed values to see if the statistical differences between the systems changed.

Also, only for runoff losses (runoff volume, total N, total P, and the dissolved fractions of both nutrients) we also conducted analyses of covariance (ANCOVAs) to determine whether geometric shape differences among the 12 watersheds improved the significance of system differences each year and on average across years. We assessed the significance of the linear relationship between each measurement and the covariables mean slope, length from the highest elevation point to the H-flume, mean and maximum flow length, a form factor (area divided by the square of the length), elongation ratio (diameter of a circle with the same area as the watershed divided by the length), and a compactness coefficient (perimeter divided by the circumference of an equivalent circular area). The ANOVAS of log-transformed values and ANCOVAs sometimes improved the significance of treatment effects, and these instances are indicated in tables or figures.

RESULTS

Soil-Test Phosphorus

Table 1 shows averages for Bray-1 and Mehlich-3 methods using the standard colorimetric determination of extracted P, which measures similar P concentrations for both extractants. Olsen P results are not shown because correlated well with the Bray-1 and Mehlich-3 test results since no topsoil was calcareous. Results shown for 2015 (corn) are from samples taken in the spring of that year but for the following crops samples were taken in the fall of the previous year. Samples taken in fall 2016 (for corn in 2017) and fall 2018 (for corn in 2019) were taken before the P fertilizer was applied in the fall of those years.

Soil-test P to a 15-cm depth (Table 1) ranged from the High Optimum to Very High interpretation categories (Mallarino et al., 2013) and there were no statistically significant differences between tillage systems in any year with or without the cover crop ($P \leq 0.10$). However, the means across all years showed slightly higher soil-test P levels without the cover crop.

For the top 0-5 cm depth (Table 1) there were more significant differences, however, and sometimes also a significant interaction between tillage system and the cover crop. The interaction was evident in the by year results because the tillage systems differed in 2015 when soil-test P was higher for no-till than for tillage without the cover crop but also differed in 2018 and 2019 when it was higher for tillage than for no-till with the cover crop. Soil-test P was higher without the cover crop in two years for no-till and in three years for tillage. On average across the six years, soil-test P differed between tillage systems only without the cover crop which was higher for tillage and was higher for both tillage systems without the cover crop, but the difference was proportionally larger for no-till than for tillage.

Table 1. Soil-test P at two sampling depths before each crop (averages of the Bray-1 and Mehlich-3 test results). †

Year	Crop	Cover Crop §	0-5 cm Depth No-till	0-5 cm Depth Tillage	0-15 cm Depth No-till	0-15 cm Depth Tillage
			Soil-Test P (ppm)			
2015	Corn	No	73a	66a‡	39a	35
		Yes	54b	55b	29b	31
2016	Soybean	No	51	47	28	27
		Yes	40	44	27	25
2017	Corn	No	43	42a	22	26
		Yes	37	31b	21	20
2018	Soybean	No	74	70	47a	49
		Yes	66	77‡	35b	41
2019	Corn	No	72a	66	38a	34
		Yes	48b	58‡	24b	26
2020	Soybean	No	53	54a	27	30
		Yes	47	43b	24	27
Means across years§		No	61a	57a‡	34a	34a
		Yes	49b	51b	26b	28b

† Samples for the 2015 (corn) were taken in the spring but for the following crops were taken in the fall of the previous year and before any P application watersheds.

‡ Significant difference between tillage systems ($P \leq 0.10$).

§ Different letters in a column indicate different cover crop effects ($P < 0.10$).

Precipitation During the Study

Table 2 shows the precipitation occurring for various periods of time during the study. We defined the crop-year annual precipitation as the amount occurring from October 1 of one year to September 30 of the next because it is the most relevant for corn and soybean due to Iowa climate and these crops cycle. The subtotals calculated for several other periods are relevant to interpret the growth of the crops and occurrence of runoff events. The long term (1995-2015) average annual rainfall for the nearest weather station to the research site distant 12.3 km for each crop year was 988 mm. Therefore, the total annual precipitation at the site was near normal in 2015 and 2016, slightly below normal in 2019, far below normal in 2017 and 2020, and higher than normal in 2018.

Table 2. Precipitation during each of six crop years for different periods of time.

Crop Year	Oct.-Sep.†	Oct.-March	April	May	June	July-Sep	May-Sep.
	mm						
2015	924	80	86	116	168	474	759
2016	1017	286	85	111	43	488	642
2017	663	198	80	138	61	185	384
2018	1166	272	43	91	322	438	852
2019	787	298	51	169	88	182	439
2020	389	197	25	55	25	87	167

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

Cereal Rye Cover Crop Biomass Yield and Nutrient Recycling

Table 3 shows the cereal rye aboveground biomass dry matter (DM) yield and the N and P accumulated and recycled to the soil at its termination. The tillage system did not affect cover crop biomass yield or N and P recycled to the soil in any year of the study ($P < 0.10$). The cereal rye aboveground biomass yields as well as amounts of N and P accumulated and recycled to the soil were the lowest in 2019 and 2020 and were much lower than normal for central Iowa. This resulted from dry surface soil at and after the rye overseeding that resulted in poor germination or dry early spring rainfall that limited growth despite a seeding rate of 168 kg/ha (higher than recommended). The cereal rye yield and nutrient recycling were approximately normal for central Iowa in 2015, 2017, and 2018 and were higher than normal in 2016.

Table 3. Cereal rye dry matter biomass yield and N and P recycled. †

	Biomass Yield			Accumulated N			Accumulated P		
Termination	NT	Till	Mean	NT	Till	Mean	NT	Till	Mean
	-- kg DM/ha --			--- kg N/ha ---			--- kg P/ha ---		
4/15/2015	2873	2695	2784	76	75	76	28	27	28
4/26/2016	3615	3843	3729	66	69	68	25	27	26
4/13/2017	2212	2629	2421	57	80	69	21	31	26
5/10/2018	2360	2734	2547	50	75	63	15	19	17
5/15/2019	762	678	720	27	32	30	3	4	4
5/30/2020	477	322	400	15	10	13	2	1	2
Means	2050	2150	2100	49	57	53	16	18	17

† There were no significant differences among systems in any year or for means ($P \leq 0.10$)

Crop Grain Yield and Nutrient Removed with Harvest

Table 4 summarizes results for crop grain yields. Corn yields were good in all years and there were statistically significant differences in 2015 and 2017, when yield was the highest for tillage without a rye cover crop, intermediate for no-till without the cover crop, and the lowest for both tillage systems with the cover crop.

Table 4. Crop grain yield in the six years and dates of the rye cover crop termination and crop planting.

			Rye Termination Date To			Grain Yield† No Cover Crop		Grain Yield† With Cover Crop	
Crop	Year	Planting Date	Tillage	Planting		No-Till	Tillage	No-Till	Tillage
			----- Days -----			------------------ Mg/ha ------------------			
Corn	2015	May 1	14	16		11.12b†	12.10a	9.14c	9.67c
	2017	May 8	24	25		14.21ab	14.66a	13.43c	13.88c
	2019	Jun 4	48	49		12.71	12.87	12.63	12.73
					Means	12.68b	13.21a	11.7c	12.09c
Soybean	2016	May 20	10	24		3.78a	3.95a	3.41b	3.39b
	2018	May 18	6	8		2.15b	2.68a	2.17b	2.38b
	2020	May 12	11	12		2.99	3.10	2.89	2.97
					Means	2.97b	3.24a	2.83b	2.92b

† Different letters indicate significant yield differences within each row ($P < 0.10$).

Significant corn yield reductions with no-till or with a cereal rye cover crop were not surprising because have been observed before. Soybean yield reductions with no-till or a cereal rye cover crop have been observed only occasionally, but were consistent in this study. The days between the cover crop termination and planting and the planting operations (Table 4) and rainfall (Table 2) did not explain the soybean yield reductions, but in 2016 and 2018 the soybean canopy did not close the gaps between rows until late August for the no-till and cover crop systems probably due to exceptionally thick cover crop residue cover in 2016 and excessive June rainfall in 2018.

Table 5 shows that amounts of N and P removed with corn and soybean grain harvest approximately followed the grain yield rankings for the systems. On average across the corn years the amounts of N and P removed were the largest for tillage (159 kg N/ha and 36.1 kg P/ha), the lowest for no-till with a cover crop (a 15% reduction for N and 13% reduction for P), and intermediate for the other two systems. On average across the soybean years the amounts of N and P removed also were the largest for tillage (168 kg N/ha and 16.1 kg P/ha), the lowest for no-till with a cover crop (a 14% reduction for N and 10% reduction for P), and intermediate for the other two systems. The soybean P removed differences between the systems were much smaller than for N removed and were also smaller than for P removed by corn.

Soil, Nitrogen, and Phosphorus Concentrations in Surface Runoff

The concentrations in runoff of soil (total solids), dissolved-reactive P (DRP), total P (TP), total N (TN), ammonium, and nitrate varied greatly between the five years with measurable runoff (none in 2020) and between systems and there were few statistical significances (not shown). Numerically, in most years the ranking of the weighted concentrations were the greatest for tillage without the cover crop and the lowest for no-till with the cover crop but the ranking of concentrations for the other systems varied greatly across the years (not shown).

Table 5. Nitrogen and phosphorus removed with harvest each year of the study.

			N removed		P removed	
Crop	Year	Cover Crop	No-Till	Tillage	No-Till	Tillage
			------ kg N/ha ----		------ kg P/ha -----	
Corn	2015	No	117b	141a	30.5b	33.2a
		Yes	98c	101c	24.6c	26.0c
	2017	No	178a	185a	41.9ab	42.8a
		Yes	160b	172ab	37.7b	41.8ab
	2019	No	154	150	31.8	32.1
		Yes	146	152	31.8	30.8
	Means	No	150b	159a	34.7ab	36.1a
		Yes	134c	142c	31.3c	32.9bc
Soybean	2016	No	188a	198a	19.4a	19.3a
		Yes	172b	171b	16.0b	18.0ab
	2018	No	112b	143a	10.6b	12.7a
		Yes	111b	123ab	10.6b	11.3ab
	2020	No	159	164	15.7	16.4
		Yes	151	156	15.2	16.2
	Means	No	153b	168a	15.2a	16.1a
		Yes	145c	150bc	14.0b	15.2a

† Different letters indicate significant differences by nutrient and year ($P < 0.10$).

Interpretations of concentrations of soil or nutrients in surface runoff require careful interpretations because are greatly affected by the runoff volume. Table 6 shows the weighted average concentrations of all runoff measurements across the five years with runoff (2015 through 2019). Statistically significant differences between systems ($P \leq 0.10$) were observed only for soil, total P, total N, and dissolved ammonium. The soil and total P concentrations were the highest for tillage without the cover crop, intermediate for tillage with the cover crop, and the lowest (and statistically similar) for no-till with or without the cover crop. The total N concentration was the highest (and statistically similar) with tillage with or without the cover crop and the lowest (and statistically similar) for no-till with or without the cover crop. The ammonium concentration was the highest for tillage without the cover crop and the lowest for the other three systems although numerically was intermediate for tillage with the cover crop.

Table 6. Weighted mean concentrations in runoff of several measurements across five years.

System	Soil	DRP†	Total P	NO_3-N	NH_4-N	Total N
	g/kg	-------------------------	-------------------------	mg/kg	-------------------------	-------------------------
Tillage no cover crop	1.17a	0.55	1.81a	1.31	0.99a	7.65a
Tillage with cover crop	0.71b	0.55	1.48ab	1.22	0.51b	6.52a
No-till no cover crop	0.23bc	0.41	0.98b	0.50	0.35b	3.59b
No-till with cover crop	0.20c	0.52	1.04b	0.64	0.37b	3.77b
Statistics ($P = F$)	0.01	0.93	0.04	0.032	0.06	0.03

† DRP, dissolved reactive P.

‡ Numbers in each column followed by the same letter do not differ at $P \leq 0.10$

Surface Runoff Volume

Table 7 summarizes the amounts of runoff (expressed as depth) in each year of the study when measurable runoff was observed. The runoff in 2015 and 2019 were near expectations for the rainfall patterns (Table 2) and slopes at the site. Runoff was much lower than expected in 2016 and 2017. In 2016 low runoff with normal annual rainfall is explained by numerous low-intensity rainfall events that produced little runoff and very low runoff in 2017 is explained mainly by severe drought for periods without soil cover by the crops canopy (Table 2). In 2020 there was no measurable runoff any time because of extreme drought during the entire year (Table 2). The far highest runoff occurred in 2018, when rainfall was much higher than normal in June and July (Table 2).

Table 7. Amount of runoff in the six years of the study for each system. †

		No Cover Crop		With Cover Crop	
Year	Crop	No-Till	Till	No-Till	Till
		-------------------------	mm	-------------------------	
2015	Corn	54	58	49	46
2016	Soybean	15	10	14	4
2017	Corn	0.5	1.4	0.2	1.2
2018	Soybean	96	197	79	104
2019	Corn	39	25	36	10
2020	Soybean	0	0	0	0
Means across years		34b	49a	30b	28b

† Systems differed ($P \leq 0.10$) only for means across the six years.

Deficient or excessive rainfall introduced high runoff variability and there were no statistically significant differences between systems in any year ($P \leq 0.10$). Numerically, runoff in 2018 was far the highest for tillage without the cover crop and differences in other years were much smaller and inconsistent. On average across the six years, runoff was the highest ($P \leq 0.10$) for tillage without the cover crop (49 mm) and the lowest (and statistically similar) for the other three systems. The systems tillage with the cover crop and no-till without or with the cover crop reduced runoff to 57, 70, and 61 percent, respectively, of the runoff for tillage without the cover crop.

Table 8 summarizes annual losses with runoff for all measurements. There were large loss differences between years but few statistical significances between treatments ($P \leq 0.10$) with or without analyses of variance or covariance using the watershed shape covariables. In 2015, only soil and total N losses differed between the systems. Soil losses were the highest for tillage without the cover crop, intermediate (and statistically similar) for tillage with the cover crop and no-till without the cover crop, and the lowest for no-till with the cover crop. Total N was the highest for tillage without the cover crop and the lowest (and statistically similar) for the other three systems.

Table 8. Runoff losses of all measurements for each year when there was runoff (none in 2020).

Year	System	Soil	DRP†	Total P	NO_3-N	NH_4-N	Total N
		kg/ha	------------------------	g/ha	--------	--------	--------
2015	Tillage no cover crop	204a	227	347	404	73	2072a
	Tillage with cover crop	116ab	218	293	488	49	1267b
	No-till no cover crop	108ab	172	243	232	98	1203b
	No-till with cover crop	82b	185	262	451	72	1240b
$P \leq F$ (form factor covariable)		0.07	ns	ns	ns	ns	0.07
2016	Tillage no cover crop	45	24b	174	8	15a	270
	Tillage with cover crop	20	10b	66	0	2b	120
	No-till no cover crop	37	23b	255	13	11a	330
	No-till with cover crop	30	44a	246	6	7ab	201
$P \leq F$ (mean flow covariable)		ns	0.09	ns	ns	0.08	ns
2017	Tillage no cover crop	15a	9	22a	12a	21a	93
	Tillage with cover crop	7ab	3	17a	1b	3b	75
	No-till no cover crop	1b	4	5b	0b	1b	10
	No-till with cover crop	0.2b	0	2b	0.2b	1b	9
$P \leq F$ (no covariable)		0.08	ns	0.09	0.08	0.05	ns
2018	Tillage no cover crop	1582a	874	2347	2502	694a	10279a
	Tillage with cover crop	529ab	695	1291	1059	524a	7848ab
	No-till no cover crop	317b	471	1149	546	309b	2894ab
	No-till with cover crop	201b	436	825	855	148b	2801b
$P \leq F$ (mean flow covariable)		0.04	ns	ns	ns	0.09	0.07
2019	Tillage no cover crop	860a	279	1070	874	523	4721
	Tillage with cover crop	156b	116	276	382	171	1228
	No-till no cover crop	147b	580	792	916	681	2386
	No-till with cover crop	120b	446	615	717	630	2135
$P \leq F$ (no covariable)		0.07	ns	ns	ns	ns	ns

† DRP, dissolved reactive P.

In 2016 losses of all runoff fractions were lower than in 2015, and only DRP and ammonium losses differed between the systems. The DRP losses were the highest for no-till with a cover crop and the lowest (and statistically similar) for the other systems. Ammonium loss was the highest and statistically similar for both tillage systems without the cover crop, intermediate for no-till with the cover crop, and the lowest for tillage with the cover crop.

In 2017 losses of soil, P, and N were very low because of drought (Table 2) and soil, total P, nitrate, and ammonium losses differed between the systems. Soil losses were the highest for tillage without the cover crop, intermediate for tillage with the cover crop and the lowest (and statistically similar) for no-till with or without the cover crop. Total P losses were the highest (and statistically similar) for tillage with or without the cover crop and the lowest (and statistically similar) for no-till with or without the cover crop. The dissolved nitrate and ammonium losses were the highest for tillage without the cover crop and the lowest (and statistically similar) for the other systems. Although total N losses were not statistically different among the systems, numerically losses were much higher for tillage than with no-till with or without the cover crop.

In 2018, losses of soil, P, and N were the highest of all years because of very high rainfall mainly in June and July (Table 2) and only soil, ammonium, and total N losses differed between the systems. Soil losses were the highest for tillage without the cover crop, intermediate for tillage with the cover crop and the lowest for no-till with or without the cover crop. Ammonium losses were the highest for tillage with or without the cover crop and the lowest for no-till with or without the cover crop. Total N losses were the highest for tillage without the cover crop, intermediate (and statistically similar) for tillage with the cover crop and no-till without the cover crop, and the lowest for no-till with the cover crop. Although differences between the systems did not attain statistical significance for DRP, total P, and nitrate, numerically the losses were by far the highest for tillage without the cover crop, intermediate for tillage with the cover crop, and the lowest for no-till with or without the cover crop.

In 2019, losses of soil, N, and P were the second highest after losses in 2018 but only the soil losses were statistically different between the systems. Soil losses were the highest for tillage without the cover crop and the lowest (and statistically similar) for the other three systems. Although differences between the systems did not attain statistical significance for the other runoff fractions, numerically the total P and total N losses were by far the highest for tillage without the cover crop than for the other systems.

The annualized runoff loads across the five years with measurable runoff are shown in Table 9. Soil, total P, dissolved ammonium, and total N differences between systems were statistically significant ($P \leq 0.10$). Soil losses were highest for tillage without the rye cover crop (541 kg/ha), intermediate for tillage with the cover crop and no-till without the cover crop, and the lowest for no-till with the cover crop. The systems tillage with the cover crop and no-till without or with the cover crop reduced soil losses by 69, 77, and 84 percent, respectively, of the loss for tillage without the cover crop.

Table 9. Annualized average runoff losses of all measurements across the five years when there was measurable runoff.

System	Soil	DRP†	Total P	NO_3-N	NH_4-N	Total N
	kg/ha	-------------------------	g/ha		-------------------------	
Tillage no cover crop	541a	283	792a	760	265a	3488a
Tillage with cover crop	166ab	208	389b	386	150b	2108ab
No-till no cover crop	122ab	250	489b	341	220b	1366b
No-till with cover crop	87b	222	390b	406	172b	1278b
$P \leq F$ (mean flow covariable)	0.04	ns	0.10	ns	0.03	0.08

† DRP, dissolved reactive P.

The total P losses were highest for tillage without the rye cover crop (792 g/ha) and the lowest (and statistically similar) for the other three systems. The systems tillage with the cover crop and no-till without or with the cover crop reduced P losses by 51, 38, and 51 percent, respectively, of the loss for tillage without the cover crop. Although DRP losses were not statistically significant, numerically losses were the highest for tillage without the cover crop (283 g/ha) and the other systems reduced losses by 12 to 26 percent. Therefore, these results across all years clearly showed that no-till with or without the cover crop and use of a cover crop with tillage greatly reduced DRP and total P losses. These results for DRP losses, although not statistically significant, are very important for Iowa because surveys and research in Ohio and Ontario have suggested that no-till management increases the dissolved P loss from fields and a Kansas study with no-till showed that cover crops increase DRP losses. This and other studies in Iowa demonstrated that in Iowa, no-till almost always increased the proportion of dissolved P loss of the total runoff P, but seldom the total dissolved P losses.

The dissolved ammonium and total N losses also were the highest for tillage without the cover crop and the lowest for the other three systems. For ammonium, the systems tillage with the cover crop and no-till without or with the cover crop reduced losses by 44, 17, and 35 percent, respectively, of the loss for tillage without the cover crop (265 g/ha). For total N, the systems tillage with the cover crop and no-till without or with the cover crop reduced losses by 40, 61, and 63 percent, respectively, of the loss for tillage without the cover crop (3488 g/ha). Although dissolved nitrate losses were not statistically significant, numerically losses were the highest for tillage without the cover crop (760 g NO_3-N/ha) and the other systems reduced losses by 47 to 55 percent. Its noteworthy that although not significant, the cover crop reduced nitrate losses with tillage but increased losses with no-till, which it is difficult to explain. These results for total N and the dissolved N fractions are very relevant because this is the only study in Iowa and the north central region that has evaluated the combined effects of tillage systems and cover crops on loss of total N and dissolved N forms with runoff.

An important result was that for all runoff losses, including dissolved N and P fractions, reductions by the cover crop were proportionally much higher for tillage than for no-till. Therefore, use of cover crops is proportionally more beneficial with tillage than with no-till management.

RAINFALL SIMULATIONS IN 2017 AND 2018

Due to extremely low rainfall and runoff during in spring 2017 and again in spring 2018, we decided to conduct rainfall simulations on all watersheds in case drought would continue using a rainfall simulator and techniques used for the National Runoff P Project in the 2000s and also used in a previous INRC project. The simulations were conducted at the V1-V2 growth stage of corn or soybean in all watersheds when all the treatments had been applied and normally is the time of the year when fields are more vulnerable to soil (total solids) and nutrient losses with runoff. The runoff samples were analyzed for the same N and P fractions and methods used for the field project.

In 2018, after we finished the rainfall simulations during the dry spring, there was very high runoff and both soil and nutrient losses in the watersheds during June and July (Tables 2 and 7) so results for 2018 are not shown, and Table 10 shows results of rainfall simulations conducted in 2017.

The amount of runoff was the highest without the cover crop and the lowest with the cover crop for both tillage systems (the tillage effects were not significant at $P \leq 0.10$). The soil and total P losses were the highest for tillage without the cover crop and the lowest with no statistical differences for the other three systems. The DRP losses were not statistically significant between systems but numerically followed the same ranking than for total P and were about twice for tillage without the cover crop than for other systems. The dissolved nitrate losses the lowest for tillage with the cover crop and the lowest for the other three systems. The dissolved ammonium losses were not statistically significant between systems but numerically losses were more than twice for no-till with or without the cover crop than for tillage with or without the cover crop. The total N losses were not statistically significant but numerically were the highest for tillage without the cover crop, intermediate (and not statistically significant) for no-till with or without the cover crop, and the lowest for tillage with the cover crop.

Table 10. Losses of the N and P fractions in runoff for field rainfall simulations conducted in May of the droughty year 2017.

System	Runoff	Soil	DRP†	Total P	NO_3-N	NH_4-N	Total N
	mm	kg/ha	g/ha				
Tillage no cover crop	22a	433a	230	455a	1567a	132	3282
Tillage with cover crop	10b	209b	42	212b	770b	142	1660
No-till no cover crop	22a	192b	75	268b	1975a	455	2640
No-till with cover crop	12b	107b	91	250b	1864a	352	2464
$P \leq F$	0.01	0.05	ns	0.08	0.07	ns	ns

† DRP, dissolved reactive P.

It is of interest to compare results for the rainfall simulations in 2017 with results from the H-flumes for the same years. The rainfall simulations showed that runoff volume was the lowest with the cover crop but there were no tillage systems differences (Table 10), whereas for the large-scale study no statistically significant runoff differences (Table 7) due to extremely low runoff that year. The rainfall simulations showed that soil, DRP, and total P losses (although not significant for DRP) were the highest for tillage without the cover crop and the lowest for the other systems, whereas the large-scale study showed extremely low losses but with approximately similar differences between systems (Table 8).

The rainfall simulations showed that dissolved nitrate losses were the lowest for tillage with the cover crop but, in contrast, the large-scale study showed that losses were the highest for tillage without the cover crop and extremely low for the other systems. The rainfall simulations showed no significant dissolved ammonium differences but numerically losses were twice or higher for both tillage systems with or without the cover crop than for the other systems, whereas the field-scale study showed significantly higher losses for tillage without the cover crop and extremely low losses for the other systems (Table 8). The rainfall simulations showed no significant total N differences but numerically losses were the highest for tillage without the cover crop, intermediate for no-till with or without the cover crop, and the lowest for tillage with the cover crop; whereas the field-scale study also showed not significant losses but were the highest for both tillage systems with or without the cover crop than for the no-till systems.

Therefore, although not all results for 2017 were comparable between the rainfall simulation and the field-scale studies, both confirmed that runoff was the highest without the cover crop, that soil, DRP, total P, and total N losses were the highest for tillage without the cover crop and were less clearly affected by the other systems or results were inconsistent between the assessment methods.

SUMMARY AND CONCLUSIONS

Results from this six-year field-scale study are very relevant for Iowa and states of the north-central region because of the lack of previous studies evaluating the effects of the four systems on soil, N, and P losses with surface runoff. Results summarized by the following points will be useful for reducing freshwater quality impairment and both N and P exports to the Gulf of Mexico and provide useful information of stacked conservation management practices impacts on corn and soybean yield in addition to the runoff losses information.

1. Soil test P was purposely maintained at levels higher than optimum for corn and soybean crops, were very variable across both systems and years. On average, soil-test P was higher with no-till than with tillage only without the cereal rye cover crop, and was also higher without the cover crop for both tillage systems but the difference was proportionally larger for no-till than for tillage.
2. The tillage system did not affect significantly the cover crop biomass yield or amounts of N and P recycled from aboveground plants parts, and were 2100 kg dry mater/ha, 53 kg N/ha, and 17 kg P/ha.
3. No-till management and use of a rye cover crop slightly reduced both corn and soybean yield. Corn yield was the highest with tillage without the cover crop, intermediate for no-till without the cover crop (a 4% reduction), and the lowest for both tillage systems with the cover crop (a 10% further reduction). Soybean yield also was the highest for tillage without a rye cover crop and the lowest for the other three systems (a 10% reduction).
4. Results confirmed the value of no-till and cover crops to reduce soil erosion. Soil losses were highest for tillage without the rye cover crop and the systems tillage with the cover crop and no-till without or with the cover crop reduced soil losses by 69, 77, and 84 percent, respectively.
5. Results proved expectations of significant sediment-bound P loss reduction by no-till and cover crops but these effects for a first time in Iowa at a field scale. Total P losses were highest for tillage without the rye cover crop and the systems tillage with the cover crop and no-till without or with the cover crop reduced P losses by 51, 38, and 51 percent, respectively.
6. Dissolved reactive P losses were not statistically different for the systems in this study but numerically losses were the highest for tillage without the cover crop and the other systems reduced losses by 12 to 26 percent. These results are very important for Iowa because surveys and research in Ohio and Ontario have suggested that no-till management increases the dissolved P loss from fields and a Kansas study with no-till showed that cover crops increase DRP losses. This study and others in Iowa demonstrated that no-till and cover crops often increase the proportion of dissolved P loss of the total runoff P but no necessarily the amount of dissolved P lost.
7. Losses of total N and both dissolved ammonium and nitrate were the highest for tillage without the cover crop. The systems tillage with the cover crop and no-till without or with the cover crop reduced ammonium losses by 44, 17, and 35 percent, respectively, total N losses by 40, 61, and 62 percent, respectively, and nitrate losses by 47 to 55 percent. The results for N losses are very relevant because this is the only study that has evaluated the combined effects of tillage systems and cover crops on loss of total N and dissolved N forms with runoff in Iowa and the north central region.
8. All runoff loss reductions by the cover crop, including the dissolved N and P fractions, were proportionally much higher for tillage than for no-till. Therefore, use of cover crops is more beneficial with tillage than with no-till management.

In conclusion, stacking the no-till and cover crops conservation practices on average reduced corn and soybean grain yield by 11 and 13 percent compared with tillage without a cover crop. However, no-till combined with a cover crop reduced soil, total P, DRP, total N, ammonium, and nitrate by 84, 51, 21, 63, and 47 percent, respectively, compared with tillage without a cover crop.

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