Received: 25 May 2022 | Accepted: 16 December 2022

DOI: 10.1002/agg2.20348

Agrosystems, Geosciences & Environment OPEN ACCESS

ORIGINAL ARTICLE

Environment

Using simulated rainfall to evaluate cover crops and winter manure application to limit nutrient loss in runoff

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Assigned to Associate Editor Hardeep Singh.

Abstract

Cover crops can be effective in minimizing nutrient losses from agricultural fields. The objective of this study was to determine the impact of cover crop (rye, *Secale cereale* L.) and winter manure application on nutrient loss in simulated rainfall runoff. A split block design study with manure (as vertical block) and cover crops (as horizontal block) was established in 2009. Two rain simulations (the first defined as "dry" and the second "wet") using sixteen 4 m^2 steel frames were conducted in May 2010. The runoff volume collected from each plot was analyzed for nitrate–nitrogen (NO_3–N), total suspended solids, total Kjeldahl nitrogen, total phosphorus, and total dissolved phosphorus. In the dry run, the concentration and load of NO_3–N were significantly lower ($p = 0.05$) in runoff with the cover crop than in no-cover crop treatment. Overall, cover crops reduced nutrient loss in concentration by 6%–48% in the dry and 8%–40% in the wet run than with no-cover crops. The concentration and load of NO_3–N were significantly higher under manure treatments in both "dry" and "wet" runoff runs compared to no-manure application. Manure application increased nutrient loss in concentration by 6%–58% in the dry and 10%–69% in the wet run than with no-manure application. This study helps us to understand the complexity of winter manure application with cover crops and potential risks of nutrient loss to surface runoff during spring in the Northern Great plains of the Dakotas.

1 | INTRODUCTION

Management systems, such as tillage and cover crops, are important to address nutrient loss with winter manure applications. Although winter manure application is not recommended, producers are still applying manure during winter due to the limited storage capacities in traditional concentrated animal feeding operations, lack of storage facilities in small farms, and more time available for manure application and spreading to avoid soil compaction (Bhandari et al., 2021; Formanek et al., 1990; Liu et al., 2017; Srinivasan et al., 2006). However, manure application during winter results in high nutrient losses in surface runoff from agricultural fields compared to spring application (Jokela et al., 2016; Kleinman et al., 2005; Little et al., 2005; Sherman et al., 2020; Srinivasan et al., 2006; Vadas et al., 2017).

Manure incorporation or using tillage practices immediately after manure application can increase manure soil

Abbreviations: BMPs, best management practices; DNR, data not reported; NO_3–N, nitrate–nitrogen; NPRP, National Phosphorus Research Protocol; RO, runoff volume; TDP, total dissolved phosphorus; TKN, total Kjeldahl nitrogen; TOC, total organic carbon; TP, total phosphorus; TSS, total suspended solids; TVSR, total volume of simulated rain applied.

interaction and reduce nutrient losses (Bhandari et al., 2021; Eghball & Gilley, 1999; Sherman et al., 2021; Yague et al., 2011). However, this practice may increase sediment bound nutrients in runoff (Little et al., 2005). Hence, coupling cover crops with manure application may help one to mitigate erosion and nutrient loss from agricultural fields. For example, Singer et al. (2007) reported coupling cover crops with the preceding corn (*Zea mays* L.) planting before manure application in late fall enhanced nutrient uptake and mitigated nutrient losses in spring runoff. Meisinger et al. (1991) indicated that cover crops can reduce surface sealing, improve infiltration, reduce erosion, improve soil fertility, and serve as excellent sinks for nitrate–nitrogen (NO_3–N). Many other studies have reported the benefit of cover crops to scavenge and reduce nitrogen (N) loss (Camberdella et al., 2010; Delgado et al., 1999; Gallaher, 1977; Hamlett & Brannan, 1991; Kaspar et al., 2007; Parkin et al., 2006; Singer et al., 2007) and phosphorus (P) loss (Burwell et al., 1975; Kleinman et al., 2005; Sharpley & Smith, 1991; Sherman et al., 2021; Thapa et al., 2018) either in runoff or drainage water when manure has been applied to the field.

Growing cover crops in cold regions can be used as a strategy to reduce soil erosion and reduce nutrient loss (Aronsson et al., 2016). Small grain cover crops such as rye (rye, *Secale cereale* L.) are widely used in the Midwest due to easy establishment and winter hardiness (Singer et al., 2008). However, cover crops adaptation in the Northern Great Plains are limited due to lack of growing season because of extreme cold weather conditions once the corn is harvested. Furthermore, little information is available regarding the impacts of coupling rye cover crops with the standing annual crop and winter manure incorporation on nutrient loss in cold climates. Improved understanding of coupling rye cover crops with winter manure injection on nutrient loss in the Northern Great Plains can help develop and support strategic use of best management practices (BMPs) on winter manure management. Investigations on the possibility of incorporating rye into the standing corn in a corn–soybean [*Glycine max* (L.) Merr.] rotation with winter manure management option are needed. The objective of this study is to determine the effect of rye cover crop planted with standing corn on the loss of winter incorporated manure applied nutrients under simulated rainfall.

Core Ideas

- If winter manure applications are necessary, use fields with cover crops.
- A cover crop reduced nutrient loss more under manure compared to non-manured systems.
- Winter manure incorporation without a cover crop increased nutrient loss in spring runoff.

2 | MATERIALS AND METHODS

2.1 | Site characteristics

In 2009, a research site was established at the Southeast Research Farm near Beresford, SD, USA. We collected soil samples to a depth of 91.44 cm. A hydraulic Giddings machine (Giddings Machine Company, Windsor, CO, USA) with a 50 mm diameter soil probe was used for soil sampling. Four soil cores were collected diagonally from each replication using a probe truck (6 cm diameter), composited, divided into 0–15, 15–30, 30–61, and 61–91 cm increments, and thoroughly mixed. Soil samples were transported to the laboratory, and approximately 20 g subsamples were used for soil moisture estimation. Total organic carbon (TOC) was determined using the weight loss-on-ignition method, and the organic matter was calculated using TOC × 1.72 formula (Schulte & Hopkins, 1996). The soil pH and soluble salts were measured in 1:2 (soil:deionized water) extract with a selective hydrogen electrode (Schofield & Taylor, 1955) and conductivity probe (Rhoades, 1982). Nitrate–nitrogen (NO_3–N) was extracted from soils with a 1 N KCl solution using a cadmium column followed by spectrophotometric measurement (Kachurina et al., 2000). The Olsen-P method was analyzed by extracting 2.5 g soil with 50 ml, 0.5 mol L^{-1} sodium bicarbonate and measuring with a spectrophotometer (Olsen, 1954). Potassium and sulfur were extracted using the Mehlich 3 solution and determined by ICP. Zinc was extracted using a DTP solution and determined by ICP. Chloride was extracted with water and determined by ion chromatography. The soil test results are presented in Table 1.

Profile moisture content of the field was determined before the initiation of the runoff study using a gravimetric method. The gravimetric soil moisture was estimated by oven drying 20-g field-moist soil samples at 105˚C for 24 h. The average gravimetric water content to the depth of 0–15 and 15–61.0 cm was 20.30% and 22.06%, respectively. No difference was found in the initial soil moisture content between cover crop treatments or the manure treatments. During April, the overall precipitation was lower than the 30-year average (Figure 1). The 4 cm of precipitation about 1 week prior to soil moisture measurements may have resulted in higher-than-average soil moisture content and masked any soil water usage by the cover crop. Rye cover crop growth in the fall was rather limited because of shading from standing corn and cool temperatures. During spring, rye growth was 20–40 cm in height. Plots had at least 70% of the surface area covered with rye. Corn residue left in the field from the previous year was estimated at 10 t ha^{-1}.

TABLE 1 Mean soil test results before planting from establishment year of cover crops and manure application, 2009

Depth (cm)	Organic matter (%)	Nitrate–nitrogen (mg kg^{-1})	Olson-P (mg kg^{-1})	Potassium (mg kg^{-1})	pH	Zinc (mg kg^{-1})	Sulfur (mg kg^{-1})	Chloride (mg kg^{-1})
0–15	4.2	6.5	19.0	305	6.4	2.6	4.5	1.5
15–30	3.4	4.0	2.0	146	6.4	1.1	3.3	0.8
30–60	3.8	4.0	1.5	141	7.1	0.190	1.3	1.3
60–90	3.6	4.0	1.5	119	7.9	0.24	2.0	1.0

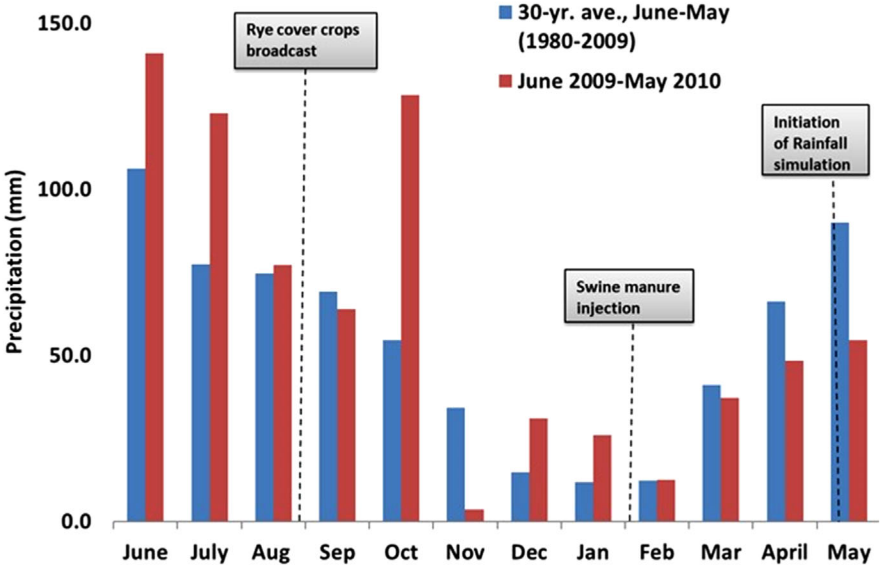

FIGURE 1 Comparison of 30-year average monthly precipitation with the study year precipitation data by month, Beresford, SD, USA

2.2 | Study design and site setup

The experimental field design consisted of a split block design (Kuehl, 2000; *p* 483–486) with four replications. Treatments consisted of cover crop (rye and no cover crop) and manure (hog manure and no manure) crossed in perpendicular to each other and randomly assigned to each of four replications. Split block design assigns equal importance to both factors (manure and cover crop). Manure treatment was considered a vertical factor, whereas cover crop was considered a horizontal factor. The crop rotation was corn–soybean–spring wheat (*Triticum aestivum* L.) with no tillage. A winter rye cover crop was broadcast seeded (80 kg ha^{-1}) on August 31, 2009 in standing corn for each of eight plots with cover crop treatment. After corn harvest, liquid hog manure was injected on December 1 and 2, 2009 at a rate of 168 kg N ha^{-1} and 144 kg P_2O_5 ha^{-1} for each of eight plots with manure treatment. Swine manure was injected into the midrow approximately 15 cm deep with a no-till applicator. The rye cover crop was well established in spring of 2010. In May 2010, sixteen 4.0 m^2 runoff collection steel frames were installed to define individual runoff plot areas with four plots on rye cover crop and manure, four on rye cover crop with no manure, four on no cover crop with manure, and four on no cover crop and no manure. The frames (Figure 2) defined two separate sampling areas of 2 m^2 and were driven into the soil about 10 cm deep as per the guidelines of the National Phosphorus Research Project (NPRP, 2001) for simulated rainfall and surface runoff studies. Soils in the inner and outer sides of the frames were firmly

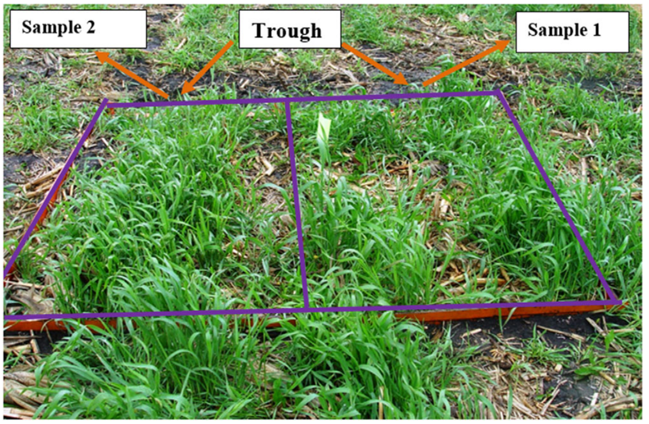

FIGURE 2 Rye cover crop growth during rainfall simulation, Beresford, SD, USA

hand-compacted after installation (about 10 cm deep) to control runoff seepage below the driven frames. Five centimeters of the frame was left above the soil surface to isolate surface runoff. Troughs were installed at the lower end of each frame to facilitate runoff collection (Figure 2) following the NPRP guidelines.

The rainfall simulator used for this study was constructed according to the guidelines developed by NPRP (2001). A single nozzle (TeeJet½ HHSS50WSQ) was used in this study based on the design of Miller (1987) that covered the 4.0 m^2 plots. The nozzle was placed approximately 305 cm above the ground to provide adequate terminal velocity of rain drops before reaching the soil surface, residue, or cover crop canopy. During the simulation, a 3 m^2 aluminum frame enclosed with tarps was used to minimize wind drift. The nozzle, wiring, and associated plumbing were attached to the aluminum frame. Pressure gauges were adjusted to achieve a target rainfall rate of 7.0 cm h^{-1} (2.75 in. h^{-1}) following standard protocol of NPRP. However, actual rainfall achieved was 6.48 cm h^{-1} (2.55 in. h^{-1}). To determine actual rainfall rate, 12 rain gauges, 6 on each subplot termed "left" and "right" were uniformly set and the rainfall simulator was run for 5 min before starting each simulation. The rainfall simulation ran until runoff started from each subplot and continued for another 30 min.

The following formula was used to calculate runoff rate for 30 min:

$$\text{Runoffrate}(\text{cmh}^{-1}) = (V/A)\,T^{-1}$$

where V is runoff water volume (cm^3); A is the plot area (20,000 cm^2); and T is the time of runoff collection (30 min).

Two rain simulations were performed from April 30 to May 10, 2010. The first was termed a dry run under existing soil moisture conditions. The second was termed a wet run and was conducted the following day (at least 12 h later) after the completion of the dry run. Natural rainfall was collected during summer 2009 until spring 2010 to use as the water source for the study. Natural rainwater contains low concentrations of flocculating cations as compared to well water and lessens the influence of soil flocculation during runoff. The concentrations of orthophosphate and total Kjeldahl nitrogen (TKN) were very low for the collected rainwater (data not reported [DNR]). Runoff for each side of the framed plots (left and right) was collected separately. Runoff water collected in a trough container was frequently vacuumed using a wet vacuum and routed by plastic pipe to a 19-L container. Water was collected for 30 min after the beginning of the runoff and the total volume was measured in liter (L).

Two subsamples from each runoff collection container were taken for further analysis and were acidified (with two drops of 10% H_2SO_4), stored in a cooler with ice packs, and refrigerated before delivering to Olsen Analytical Services Laboratory, South Dakota State University, Brookings, SD, USA. Runoff samples from each subplot were processed in the lab and analyzed for NO_3–N, total suspended solids (TSS), total P (TP), and total dissolved phosphorus (TDP) using SM 4110 B method, SM 2540 D method, and SM 4500 B & E (for TP and TDP) method, respectively (APHA, 2005). The TKN was analyzed using EPA 351.3 (Nesslerization) method (USEPA, 1983). Daily load (volume × concentration) was calculated from daily runoff volume and concentrations for each subplot. The two samples within each plot were analyzed separately, and the results were averaged for statistical analysis.

2.3 | Statistical analysis

Analysis-of-variance (ANOVA) procedure was used on measured variables to determine treatment effect. Statistical computing environment R (R Core Team, 2021) and "agricolae" package (Mendiburu, 2021) was used to analyze dataset according to split block design (Kuehl, 2000; *p* 483–486). The manure (vertical factor) and cover crop (horizontal factor) treatments were considered fixed effects, whereas replication was considered the random effect. The data was analyzed separately for dry run and wet run. A mean separation of treatment effects (where appropriate) was conducted using Fisher's LSD. Statistical significance was set up at $p \leq 0.05$.

3 | RESULTS

3.1 | Dry run

In the dry run, the coefficient of variation (CV) ranged as 18%–49%, 20%–56%, 11%–51%, 20%–87%, 26%–71%, and 17%–64% for runoff volume (RO), NO_3–N, TKN, TSS, TP, and TDP, respectively, in concentration and loads during ANOVA (DNR). The NO_3–N concentration, NO_3–N load, and TP concentration in runoff collection were three variables impacted by manure application in dry run (Table 2). All these three variables were increased ($p \leq 0.05$) by manure application.

Cover crop reduced ($p \leq 0.05$) NO_3–N concentration and load in runoff collected. There was an interaction effect by cover crop and manure for NO_3–N concentration. Cover crop presence reduced NO_3–N concentration from manure-applied plots only ($p \leq 0.05$; Table 2). The NO_3–N concentration and load in runoff was 277% and 240% greater with manure application compared to no-manure application. Similarly, the NO_3–N loss was 182% greater without cover crops than with cover crops.

TABLE 2 Analysis of variance (ANOVA) and mean separation for nutrients concentration in rainfall runoff and rainfall runoff load (dry run) as influenced by cover crop and manure application, Beresford, SD, USA, 2010

			Concentration in runoff (mg L^{-1})					Runoff load (kg ha^{-1})				
Treatments	**TVSR (L)**	**RO (L)**	**NO_3–N**	**TKN**	**TSS**	**TP**	**TDP**	**NO_3–N**	**TKN**	**TSS**	**TP**	**TDP**
Interactions												
Manure + no-cover crop	154.1^{a}	14.9^{a}	2.91^{a}	2.67^{a}	225^{a}	0.84^{a}	0.18^{a}	0.24^{a}	0.20^{a}	15.7^{a}	0.049^{a}	0.014^{a}
Manure + cover crop	166.6^{a}	17.8^{a}	1.00^{b}	2.02^{a}	129^{a}	0.39^{a}	0.18^{a}	0.09^{ab}	0.17^{a}	11.7^{a}	0.034^{a}	0.016^{a}
No manure + no-cover crop	106.5^{b}	17.6^{a}	0.74^{b}	1.75^{a}	85^{a}	0.29^{a}	0.17^{a}	0.07^{ab}	0.15^{a}	7.20^{a}	0.027^{a}	0.016^{a}
No manure + cover crop	152.0^{a}	18.6^{a}	0.29^{b}	1.92^{a}	110^{a}	0.31^{a}	0.15^{a}	0.03^{b}	0.16^{a}	8.2^{a}	0.030^{a}	0.018^{a}
Factor A—manure (vertical block)												
Manure ($n = 8$)	160.4^{a}	16.3^{a}	1.96^{a}	2.35^{a}	178^{a}	0.61^{a}	0.18^{a}	0.17^{a}	0.19^{a}	13.7^{a}	0.042^{a}	0.017^{a}
No manure ($n = 8$)	129.2^{b}	18.1^{a}	0.52^{b}	1.84^{a}	97^{a}	0.30^{b}	0.16^{a}	0.05^{b}	0.16^{a}	7.70^{a}	0.028^{a}	0.015^{a}
Factor B—cover crops (horizontal block)												
No cover crop ($n = 8$)	159.3^{a}	16.3^{a}	1.83^{a}	2.21^{a}	155^{a}	0.56^{a}	0.18^{a}	0.16^{a}	0.18^{a}	11.5^{a}	0.038^{a}	0.017^{a}
Cover crop ($n = 8$)	130.3^{a}	18.2^{a}	0.65^{b}	1.97^{a}	119^{a}	0.35^{a}*	0.18^{a}	0.06^{b}	0.17^{a}	9.97^{a}	0.032^{a}	0.015^{a}
Source of variation	ANOVA, $P > F$							ANOVA, P > F				
Manure (m) (1, 3)	0.04*	0.70	0.020*	0.08	0.07	0.04*	0.36	0.020*	0.24	0.10	0.10	0.70
Cover crop (c) (1, 3)	0.46	0.68	0.002*	0.13	0.08	0.19	0.75	0.030*	0.77	0.77	0.67	0.74
$m \times c$ (1, 3)	0.014*	0.66	0.030*	0.09	0.19	0.17	0.45	0.11	0.42	0.30	0.15	0.98

Note: Dry run = rainfall applied at the existing soil moisture condition of the field. Runoff load is calculated as runoff volume/area × concentration. $p > F$ = probability that tabular F-ratio exceeds F-ratio calculated by analysis of variance. Data in parenthesis are degree of freedom for each parameter and error associated with them for F test. p values less than 0.05 are considered significant (indicated with "*"); different letters within a column and within each factor (factor A, B, and interaction) indicate LSD values significant at the 0.05 probability level.

Abbreviations: NO_3–N, nitrate–nitrogen; RO, simulated rainfall runoff (L); TDP, total dissolved phosphorus; TKN = total Kjeldahl nitrogen; TP, total phosphorus; TSS, total suspended solids; TVSR, total volume of simulated rainfall applied.

The TP concentration in the runoff was significantly greater ($p = 0.04$) with manure application compared with no-manure application. The overall TP loss was 103% greater with manure than with no-manure application. Although not significant, the TKN, TSS, and TDP losses were greater with manure application than no-manure application in concentration and load ranging from 19% to 28%, 78% to 84%, and 0% to 13%, respectively. Likewise, the TKN, TSS, TP, and TDP losses were lower with cover crops compared to no-cover crops in concentration and load ranging from 6% to 12%, 15% to 30%, 19% to 60%, and 0% to 13%, respectively.

3.2 | Wet run

In the wet run, the CV ranged as 10%–36%, 40%–58%, 14%–33%, 14%–97%, 13%–47%, and 28%–57% for RO, NO_3–N, TKN, TSS, TP, and TDP, respectively, in concentration and loads during ANOVA (DNR). This variation in the dataset resulted in no statistical difference on most of the parameters. For example, NO_3–N concentration varied more than 100% between cover crop and no-cover crop treatment but was not statistically different (Table 3).

The NO_3–N concentration was 443% greater ($p \leq 0.05$) with manure than with no-manure treatments (Table 3). Manure application also increased the NO_3–N load by 143% ($p \leq 0.05$). Cover crops reduced NO_3–N load in runoff collection by 129% ($p \leq 0.05$; Table 3). The TSS load was significantly greater with manure application compared to no-manure application. The TKN, TSS, TP, and TDP concentration and load were greater with manure than no manure, ranging from 6% to 9%, 34% to 37%, 20% to 122%, and 23% to 100%, respectively. Likewise, the TKN, TSS, TP, and TDP concentration and load were greater with no-cover crops than cover crops, ranging from 13% to 17%, 18% to 22%, 2% to 7%, and 0% to 7%, respectively.

4 | DISCUSSION

4.1 | Runoff and nutrient loss

The total volume of simulated rain applied (TVSR) per plot ranged from 84 to 270 and 70 to 112 L in the dry and wet runs, respectively. The antecedent soil moisture was measured outside the simulated plots before the dry run and was similar in all the treatments (DNR). Nevertheless, it was not measured before the wet run to avoid soil disturbance inside the plots. The TVSR in the dry run was significantly greater with manure than without manure. The significantly greater TVSR needed with manure application treatment might be due to soil disturbance and surface roughness created because of knifing during the manure application, which increases

TABLE 3 Analysis of variance (ANOVA) and mean separation for nutrients concentration in rainfall runoff and rainfall runoff load (wet run) as influenced by cover crop and manure application, Beresford, SD, USA, 2010

	Concentration in runoff ($mg\ L^{-1}$)							Runoff load ($kg\ ha^{-1}$)				
Treatments	**TVSR (L)**	**RO (L)**	**NO_3–N**	**TKN**	**TSS**	**TP**	**TDP**	**NO_3–N**	**TKN**	**TSS**	**TP**	**TDP**
Interactions												
Manure + no cover crop	97.0[a]	39.2[a]	1.26[a]	2.03[a]	221[a]	0.36[a]	0.17[a]	0.24[a]	0.40[a]	23.5[a]	0.071[a]	0.034[a]
Manure + cover crop	94.9[a]	42.1[a]	0.54[a]	1.50[a]	85[a]	0.30[a]	0.15[a]	0.10[a]	0.31[a]	17.0[a]	0.061[a]	0.030[a]
No manure + no cover crop	86.8[a]	38.7[a]	0.42[a]	1.63[a]	74[a]	0.26[a]	0.13[a]	0.09[a]	0.32[a]	15.1[a]	0.059[a]	0.027[a]
No manure + cover crop	85.3[a]	42.5[a]	0.27[a]	1.61[a]	81[a]	0.28[a]	0.13[a]	0.05[a]	0.33[a]	14.5[a]	0.051[a]	0.030[a]
Factor A—manure (vertical block)												
Manure ($n = 8$)	90.9[a]	40.6[a]	1.90[a]	1.77[a]	103[a]	0.33[a]	0.16[a]	0.17[a]	0.35[a]	20.3[a]	0.066[a]	0.030[a]
No manure ($n = 8$)	91.2[a]	40.6[a]	0.35[b]	1.62[a]	77[a]	0.27[a]	0.13[a]	0.07[b]	0.33[a]	14.8[b]	0.055[a]	0.030[a]
Factor B—cover crops (horizontal block)												
No cover crop ($n = 8$)	86.1[a]	38.9[a]	0.84[a]	1.83[a]	97[a]	0.31[a]	0.15[a]	0.16[a]	0.36[a]	19.3[a]	0.061[a]	0.030[a]
Cover crop ($n = 8$)	95.9[a]	42.3[a]	0.41[a]	1.56[a]	82[a]	0.29[a]*	0.14[a]	0.07[b]	0.32[a]	15.8[a]	0.060[a]	0.030[a]
Source of variation	ANOVA $p > F$							ANOVA $p > F$				
Manure (m) (1, 3)	0.89	0.98	0.02*	0.32	0.17	0.11	0.19	0.03*	0.47	0.02*	0.07	0.58
Cover crop (c) (1, 3)	0.06	0.67	0.09	0.14	0.73	0.68	0.75	0.05*	0.53	0.70	0.91	0.96
$m \times c$ (1, 3)	0.44	0.84	0.22	0.22	0.29	0.30	0.60	0.23	0.38	0.45	0.35	0.48

Note: Wet run = rainfall applied after 12 h of dry run (nearly at field capacity). Runoff load is calculated as runoff volume/area × concentration. $p > F$ = probability that tabular F-ratio exceeds F-ratio calculated by analysis of variance. Data in parenthesis are degree of freedom for each parameter and error associated with them for F test. p values less than 0.05 are considered significant (indicated with "*"); different letters within a column and within each factor (factors A, B, and interaction) indicate LSD values significant at the probability level.

Abbreviations: NO_3–N, nitrage–nitrogen; RO, simulated rainfall runoff (L); TDP, total dissolved phosphorus; TKN, total Kjeldahl nitrogen; TP, total phosphorus; TSS, total suspended solids; TVSR, total volume of simulated rain applied.

water-holding capacity and soil infiltration. Rough tillage is as effective as cover crops in reducing runoff (Lolay & Bielders, 2010). Likewise, TVSR was significantly lower in no-cover crop with no-manure treatment than in cover crop treatments with or without manure (Table 2), which might be due to increased infiltration and water holding due to cover crops. Therefore, the greater amount of TVSR needed in cover crop treatments indicates prolonged runoff time after rainfall to generate runoff, decreasing runoff volume and potentially reducing nutrient loss. Studies have reported similar results with cover crops in reducing runoff and nutrient loss (Blanco-Canqui et al., 2015; Lolay & Bielders, 2010). However, there was no treatment effect on TVSR in the wet run (Table 3), which might be due to the full saturation of soil pores and similar antecedent moisture content in all treatments after the dry run.

Mean RO ranged from 14.9 to 18.6 and 38.6 to 48.5 L in the dry and wet run, respectively, during the runoff period (Tables 2 and 3). The collected runoff quantity as a percent of rainwater applied ranged from 3% to 31% in the dry and 32% to 82% in the wet run (DNR). The average RO was 17.2 L from the dry run compared to 40.6 L with the wet run. The greater RO in the wet run compared to the dry run was presumably due to the higher antecedent soil moisture for the wet run. The results indicated that antecedent soil moisture before precipitation might significantly increase the runoff volume and perhaps the nutrient loss from agricultural fields.

4.2 | Manure application effects (manure vs. no manure)

Manure application, even after 6 months, significantly increased the concentration and load of NO_3–N and the concentration of TP in runoff from the dry run (Table 2). In the wet run, the concentration and load of NO_3–N were significantly greater. Further, the TSS load due to manure application was significantly increased in the wet run (Table 3). The increased concentration and runoff load of NO_3–N and TP in runoff agrees with previous studies (Cambardella et al., 2010; Kleinmen et al., 2005; Kovar et al., 2011). Presumably, the greater NO_3–N and TP loss resulted from the additional nutrients from manure and disturbance during manure injection. However, the significantly increased TSS loads may have been due to increased soil disturbance during the dry run and exposure caused by the manure's knifing (incision made in soil surface) application. Non-manured plots were not knifed. The higher TSS load observed during wet run compared to dry run (approximately 68% more) suggests that total runoff volume collected during the wet run may be a contributing factor to this result.

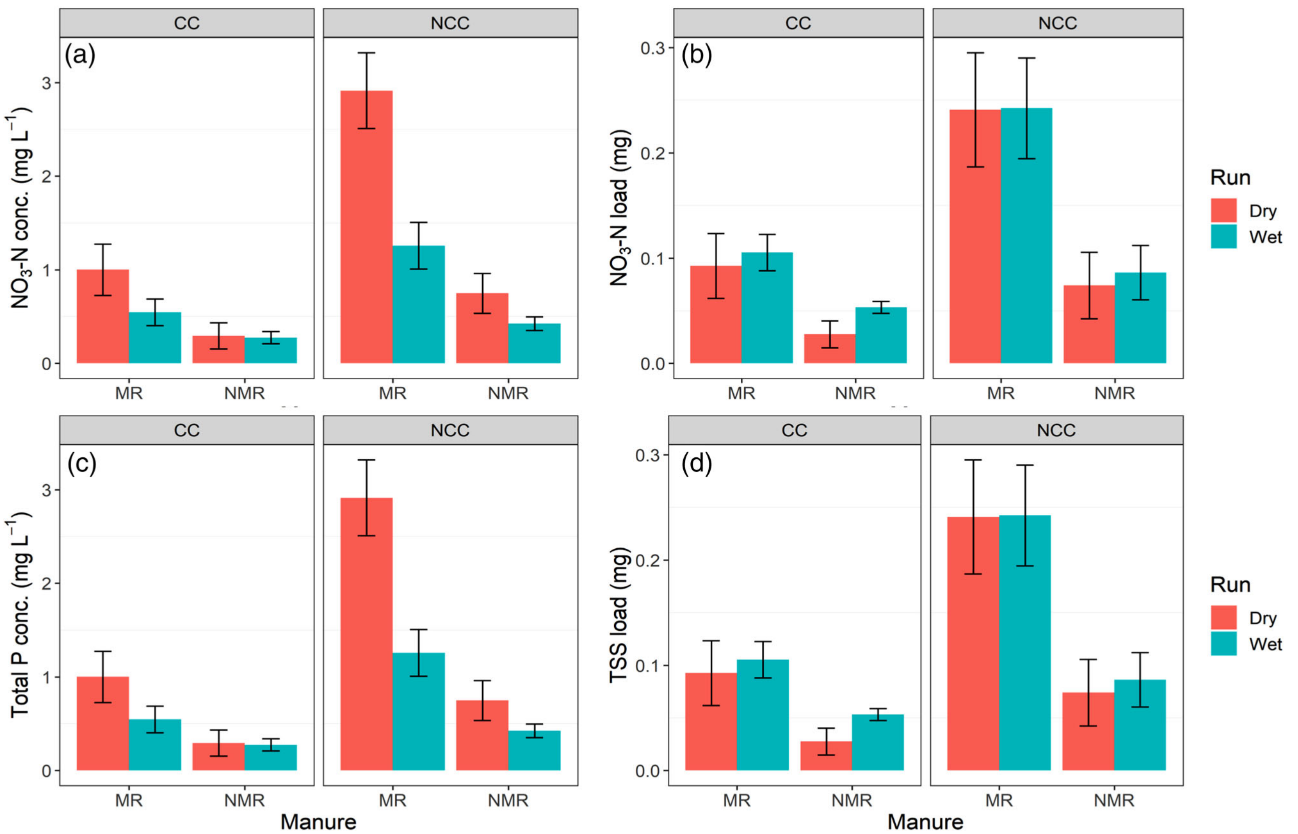

FIGURE 3 Least square means (bar chart) and their standard error (lines on the top of bar chart) after fixed effect Analysis-of-variance (ANOVA) model: (a) nitrate–nitrogen (NO_3–N) concentration, (b) nitrate–nitrogen (NO_3–N) loads, (c) total P concentration, and (d) total suspended solids (TSS) loads comparison between dry and wet runs. CC, cover crops; MR, manure application; NCC, no-cover crops; NMR, no-manure application

4.3 | Cover crop effects

The addition of the cover crop significantly lowered dry run NO_3–N concentration and load. Further, most nutrient parameters were lower with cover crops compared to no-cover crops during the dry run (Table 2, Figure 3A). The wet run results showed similar trends with lower NO_3–N load with cover crops compared to no-cover crops (Table 3, Figure 3B). Lower NO_3–N loss in both dry and wet run with cover crops reflects a lower soil nitrate level, perhaps because of N uptake by the rye growth. Singer et al. (2007, 2008) reported increased nitrogen (N) uptake by cover crops with manure applications. The results of lower nitrate and nutrient loss when coupling with a cover crop in surface runoff and subsurface drainage was supported by several studies (Carver et al., 2022; Griffith et al., 2020; Kasper et al., 2007; Meisinger et al., 1991; Parkin et al., 2006; Sharpley & Smith, 1991). The results indicate a significant impact of cover crops in mitigating nitrate loss through surface runoff. Cover crop nutrient uptake was not measured before runoff commenced in this study. However, nitrogen uptake for rye cover crop is generally about 10–15 times greater than P, indicating higher removal rates of N (Singer et al., 2008).

The cover crop presence lowered NO_3–N, TP, and TSS loss in runoff to a much greater extent when manure was applied although not always significant. Without manure, the cover crop had little effect. Cover crop growth may have lowered the higher soil NO_3–N levels that resulted from manure application. Therefore, less soil NO_3–N was available for runoff. The cover crop may have also provided a physical barrier from the simulated raindrops and protected TSS materials from leaving in runoff water. Carver et al. (2022) reported reduced sediment loss with the use of cover crops and indicated to use cover crops as site-specific tools to reduce sediment loss. Without the manure addition, there may have been less disturbed solids and less exposed soil resulting in a more negligible effect from the cover crop treatment.

4.4 | Effect of antecedent moisture, and runoff volume on nutrient loss

Runoff was generated earlier after rain was initiated in the wet run (second) than the dry (first) and resulted in greater volume than the dry rainfall simulation. The earlier runoff generation and greater runoff volume with a wet run might be due to increased antecedent moisture after the dry run (Liu et al., 2014; Schoener & Stone, 2019). Overall, the concentration of NO_3–N was greater in the dry run, especially with manure application, compared to the wet run, both with and without cover crops (Figure 3A). It might be due to the washing away of surface nutrients resulting in higher concentrations in the dry immediately before the wet run. In the wet run, less NO_3–N may be available in the runoff because of the dilution of nutrients, including potential leaching induced by high quantities of rain utilized in the dry run. However, the load of NO_3–N was greater with the wet run due to increased runoff volume (Figure 3B). Similarly, TP concentration was greater in the dry run, especially with manure application, than in the wet run, both with and without cover crops (Figure 3C). The load of TSS was greater with the wet run than the dry run regardless of manure application and cover crops use (Figure 3D). The greater loads with the wet run were likely due to higher runoff volume that was generated.

Further, the average concentrations of TKN, TSS, TP, and TDP were greater with the dry run than those measured during the wet run rainfall simulation. For instance, the concentration of TKN, TSS, TP, and TDP was greater by 25%, 42%, 46%, and 11%, respectively, with manure application in the dry run than the wet run. Similarly, the concentrations of NO_3–N, TKN, TSS, TP, and TDP were greater by 37%, 21%, 31%, 17%, and 22%, respectively, in the dry run with the presence of cover crops compared to the wet run. During the wet run, the decrease in nutrient concentration might be because of dilution due to greater runoff volume. However, loads of TKN, TSS, TP, and TDP were 84%, 48%, 57%, and 76% greater, respectively, with the wet run and manure application. Loads of NO_3–N, TKN, TSS, TP, and TDP were 17%, 112%, 58%, 88%, and 100% greater with the wet run for treatments with cover crops. The greater nutrients and sediment loads might be due to increased runoff volume during the wet run. Similar results with decreased concentration but increased surface runoff and nutrient loss with consecutive rainfall were observed by Liu et al. (2014) under simulated rainfall conditions.

5 | CONCLUSIONS

Manure application significantly increased NO_3–N loads and potential loss in runoff compared to no-manure application. Nutrient concentration at the soil surface, the intensity of soil–manure interaction, and runoff volume play an important role in nutrient loss in runoff. The nutrient loss in concentration was greater with the dry run compared to the wet run. The loads were higher with wet run than with dry run due to greater runoff volume. Manure application increased TKN, TSS, TP, and TDP in concentration by 6%–58% in the dry and 10%–69% in the wet run than no manure. Overall, cover crops reduced nutrient concentration by 6%–48% in the dry and 8%–40% in the wet run than with no-cover crops. In addition, cover crop growth reduced NO_3–N and other nutrient loss more under a manure system than in a non-manured system although not always significant. Therefore, the BMPs' use of cover crops with the standing annual crop that utilize winter manure application should be considered to limit nutrient losses to water resources for winter manure applications in the Northern Great Plains of the Dakota region to be sustainable.

AUTHOR CONTRIBUTIONS

Ammar Bhandari: Conceptualization, data curation, investigation, methodology, writing original draft, writing review and editing. **David German**: Conceptualization, methodology, data curation, project administration, resources, supervision. **Ronald Gelderman**: Project administration, resources. **Tulsi P. Kharel**: Formal analysis, writing review and editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Bhandari, A. B., Gelderman, R., German, D. R., & Kharel, T. P. (2023). Using simulated rainfall to evaluate cover crops and winter manure application to limit nutrient loss in runoff. *Agrosystems, Geosciences & Environment*, *6,* e20348. https://doi.org/10.1002/agg2.20348