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Runoff water quality characteristics following swine slurry application under broadcast and injected conditions

Nicole R. Schuster
University of Nebraska-Lincoln

Shannon L. Bartelt-Hunt
University of Nebraska-Lincoln, sbartelt2@unl.edu

Lisa M. Durso
USDA-ARS, Lisa.Durso@ars.usda.gov

John E. Gilley
USDA ARS & University of Nebraska-Lincoln, john.gilley@ars.usda.gov

Xu Li
University of Nebraska-Lincoln, xuli@unl.edu

See next page for additional authors

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Authors

Nicole R. Schuster, Shannon L. Bartelt-Hunt, Lisa M. Durso, John E. Gilley, Xu Li, David B. Marx, Amy M. Schmidt, and Daniel D. Snow

RUNOFF WATER QUALITY CHARACTERISTICS FOLLOWING SWINE SLURRY APPLICATION UNDER BROADCAST AND INJECTED CONDITIONS

N. R. Schuster, S. L. Bartelt-Hunt, L. M. Durso, J. E. Gilley,
X. Li, D. B Marx, A. M. Schmidt, D. D. Snow

ABSTRACT. *This study was conducted to measure the effects of swine slurry application method, time following slurry application, and runoff rate on selected water quality characteristics. Slurry from a commercial swine operation was broadcast or injected on field plots at a rate required to meet annual nitrogen requirements for corn. Rainfall simulation tests were conducted at five varying periods following slurry application. During each study period, three simulated rainfall events, separated by 24 h intervals, were applied for 30 min duration at an intensity of approximately 70 mm h^{-1}. Following the third rainfall simulation event, inflow was applied at the top of the plots in four successive increments to simulate greater plot lengths. Runoff samples were collected for analyses of dissolved P (DP), particulate P, total P (TP), NO_3-N, NH_4-N, total N, electrical conductivity, pH, and soil loss. The DP and TP loads of 0.35 and 0.46 kg ha^{-1} measured for the broadcast treatment were significantly greater than the 0.13 and 0.19 kg ha^{-1} obtained for the injection treatment. As time following slurry application increased from 1 to 3 days to 43 to 45 days, DP, TP, and NH_4-N loads decreased from 0.35 to 0.14, from 0.52 to 0.18, and from 2.17 to 0.14 kg ha^{-1}, respectively. Runoff rate significantly affected each of the measured water quality parameters. Runoff loads of DP, TP, and NH_4-N increased from 10.1 to 29.8, from 12.9 to 35.5, and from 13.9 to 25.1 g ha^{-1} min^{-1}, respectively, as overland flow rate increased from 2.3 to 12.6 L min^{-1}. Application method, time following slurry application, and runoff rate are important variables influencing water quality characteristics of runoff.*

Keywords. *Land application, Manure management, Manure runoff, Nitrogen, Nutrients, Phosphorus, Runoff, Soil loss, Swine manure, Water quality.*

Nutrients contained in manure can be effectively used for crop production. The application of manure has also been shown to enhance soil properties (Gilley and Risse, 2000; Eghball et al., 2004). Mitchell and Gunther (1976) reported that the addition of liquid swine manure resulted in decreased runoff and erosion rates by providing a stabilizing effect on soil surfaces. However, residual phosphorus (P) contained in manure may accumulate within soil and result in larger soil P test values. An increase in soil nutrient content may cause greater runoff nutrient concentrations (Gilley et al., 2007). However, soil nutrient values may not significantly impact nutrient losses when rainfall occurs soon after manure application, since the contribution to nutrient runoff supplied by the manure may be substantially larger than that provided by soil (Eghball et al., 2002).

The U.S. Environmental Protection Agency has identified numeric nutrient criteria for both nitrogen (N) and P to protect aquatic systems (USEPA, 2000a, 2000b). Nitrogen entering surface water has the ability to produce hypoxic zones if transported to salt water systems like the Gulf of Mexico (Turner et al., 1997). Additionally, animal manure application in excess of crop nutrient requirements can increase the potential for groundwater contamination (Mathers et al., 1975).

Three important variables that have been reported to influence nutrient transport in runoff from areas on which swine slurry has been applied include application rate, application method, and length of time following slurry addition. Edwards and Daniel (1993) found that runoff concentrations and event mass losses of selected constituents both increased approximately linearly with application rate when slurry was applied to fescue grass plots. Losses of DP in runoff during the spring thaw period were determined by Gessel et al.

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The authors are **Nicole R. Schuster,** Former Graduate Student, Department of Biological Systems Engineering, University of Nebraska, Lincoln, Nebraska; **Shannon L. Bartelt-Hunt,** Associate Professor, Department of Civil Engineering, University of Nebraska, Omaha, Nebraska; **Lisa M. Durso,** Research Microbiologist, and **John E. Gilley, ASABE Member,** Research Agricultural Engineer, USDA-ARS Agroecosystem Management Research Unit, Lincoln, Nebraska; **Xu Li,** Associate Professor, Department of Civil Engineering, **David B. Marx,** Emeritus Professor, Department of Statistics, and **Amy M. Schmidt, ASABE Member,** Assistant Professor, Department of Biological Systems Engineering, University of Nebraska, Lincoln, Nebraska; **Daniel D. Snow,** Research Associate Professor, Nebraska Water Center, University of Nebraska, Lincoln, Nebraska. **Corresponding author:** John E. Gilley, USDA-ARS, 251 Chase Hall, University of Nebraska, Lincoln, NE 68583-0726; phone: 402-472-2975; email: John.Gilley@ars.usda.gov.

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(2004) to increase with greater application when slurry was applied at rates that were 0, 0.5, 1, and 2 times the amount of P recommended for a corn-soybean rotation.

Tabbara (2003) reported that 24 h after surface application of slurry, incorporation by disking reduced concentrations and loads of dissolved reactive phosphorus (DRP) and TP by as much as 30% to 60%. Incorporation of slurry by disking was found by Allen and Mallarino (2008) to substantially reduce concentrations and loads of DRP and TP for tests conducted 24 h and 10 to 16 days following slurry addition. Gilley et al. (2013b) determined that the DP load on plots where slurry was applied to meet annual N requirements for corn was significantly greater on the broadcast treatments than on the disked and injected treatments.

Daverede et al. (2004) measured significant reductions in concentrations and loads of DRP and TP between the one-month and six-month sampling dates on plots where slurry was broadcast. Concentrations of DP, TP, and NH_4-N, in general, were reported by Gilley et al. (2007) to decline throughout the year on plots where slurry was broadcast. Allen and Mallarino (2008) found that for rainfall simulation tests conducted five to six months following slurry application, runoff P loads on the plots where slurry was applied were similar to the control plots that did not receive slurry.

Previous studies have shown that the greatest potential for nutrient transport results from a rainfall event occurring soon after application of swine slurry. Additional information is needed to determine how rapidly runoff nutrient transport is reduced following slurry addition. The objective of this study was to measure the effects of swine slurry application method, time following slurry application, and runoff rate on selected water quality characteristics.

MATERIALS AND METHODS

STUDY SITE CHARACTERISTICS

This field study was conducted from June through August 2014 at the University of Nebraska-Lincoln Rogers Memorial Farm, located 18 km east of Lincoln, Nebraska, in Lancaster County. The Aksarben silty clay loam soil at the site (fine, smectitic, mesic Typic Argiudoll) contained 15% sand, 48% silt, and 37% clay (Kettler et al., 2001). The organic matter and total carbon content of the soil were 3.5% and 1.5%, respectively (Nelson and Sommers, 1996). This soil developed in loess deposits under prairie vegetation and is considered a benchmark soil for this region.

The study site has been cropped using a no-till management system under a corn (*Zea mays* L.), grain sorghum (*Sorghum bicolor* (L.) Moench), soybean (*Glycine max* (L.) Merr.), and winter wheat (*Triticum aestivum* L. cv. Pastiche) rotation. Corn was planted during the 2013 season, and the area was left undisturbed following harvest in October 2013. Herbicide (glyphosate) was applied to the site as needed to control weed growth. Manure has not been added at the study area since at least 1966. Swine slurry is often applied in this region in the spring when the soil is no longer frozen but before cropland areas are seeded. Thus, several weeks may expire following slurry application before the subsequent row crop begins to provide a vegetative cover.

PLOT PREPARATION

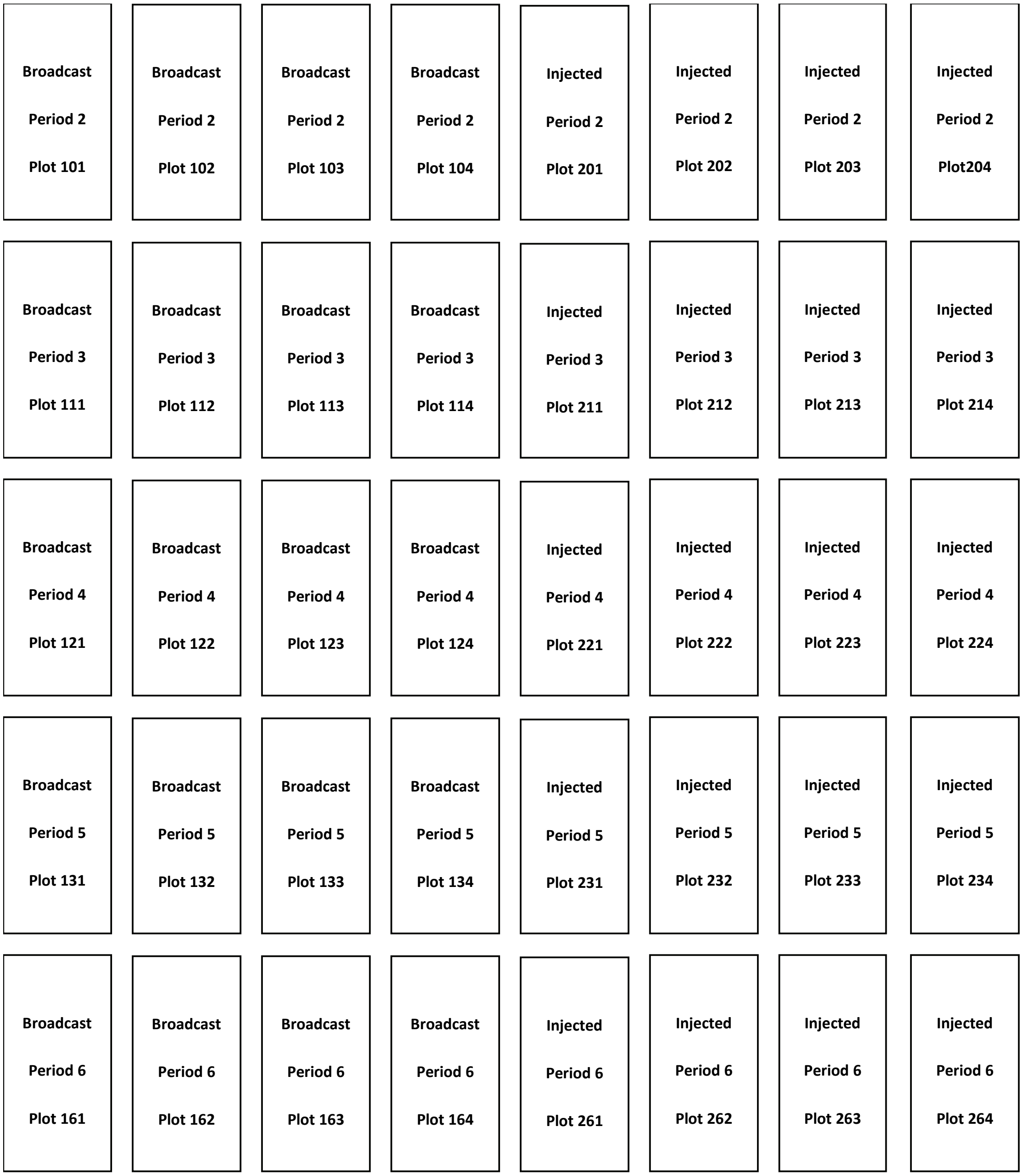
Experimental treatments included manure application method (broadcast and injected), the number of days following slurry application before the rainfall simulation tests were initiated, i.e., 1 to 3 days (1-3 July 2014), 8 to 10 days (8-10 July 2014), 15 to 17 days (15-17 July 2014), 22 to 24 days (22-24 July 2014), and 43 to 45 days (12-14 August 2014), and runoff rate (2.3, 6.0, 9.5, and 12.6 L min^{-1}) (fig. 1). A commercial operator was hired to apply slurry at the experimental site on 30 June 2014. The three-axle slurry applicator was 9.1 m long and had a capacity of 27,750 L. A four-wheel-drive tractor that was 6.6 m long was used to pull the slurry applicator. The large dimensions of the applicator and tractor made it necessary to establish the broadcast, check, and injection plots in separate blocks along the hillslope.

A V-shaped chisel (horizontal sweep) implement with a six-row applicator and row spacing of 76 cm was used to inject the swine slurry. Although not measured directly, it is estimated that approximately 70% to 85% of the surface residue remained following slurry injection (Hanna et al., 1995). For the broadcast treatment, the applicator was raised above the soil surface while maintaining a steady speed and uniform slurry flow rate. The slurry was applied along the contour at a rate of approximately 46,800 L ha^{-1}. Available N was added at a rate of approximately 180 kg N ha^{-1}, assuming that the N availability from swine slurry is 70% of the total amount of N in the slurry (Gilbertson et al., 1979).

Swine slurry was applied to 40 plots, each 0.75 m wide × 2 m long. Block 2 contained 20 plots on which slurry was broadcast, and slurry was injected on the 20 plots included in block 3. Rainfall simulation tests were conducted on eight plots during each of five test periods (fig. 1). Four of the plots were located in the broadcast block, and four plots were established in the adjoining slurry injection block. The eight plots examined during a selected test period were not used during subsequent investigations. The plots were not protected from natural rainfall. The only rainfall during the study period on the plots where slurry was applied occurred on 3 July 2014 (2.5 mm) and 18 July 2014 (2.3 mm). The slope gradient (and standard deviation) of the 20 plots on the broadcast block and 20 plots on the injection block was 5.8% (1.9%) and 7.6% (1.7%), respectively.

The experimental tests on the plots on which slurry was applied were conducted over a six-week interval. It was important to determine whether changes in runoff water quality during the study period resulted from slurry application or varying soil conditions. Therefore, additional rainfall simulation tests were initiated seven days before (24 June 2014) and 29 days following slurry application (29 July 2014) on an adjoining block (block 1) where slurry was not applied (fig. 2). Eight control plots were examined during each of these two additional study periods. Therefore, tests were conducted on 16 separate control plots as part of this investigation. The slope gradient and standard deviation of the 16 plots in block 1 was 7.4% (0.9%). A rainfall event with 20.3 mm of precipitation was recorded on 27 June 2014.

Swine slurry was collected from a deep pit on a commercial 8000-head wean-to-finish swine operation in north central Nebraska just prior to field application. Samples of the



Broadcast Period 2 Plot 101	Broadcast Period 2 Plot 102	Broadcast Period 2 Plot 103	Broadcast Period 2 Plot 104	Injected Period 2 Plot 201	Injected Period 2 Plot 202	Injected Period 2 Plot 203	Injected Period 2 Plot204
Broadcast Period 3 Plot 111	Broadcast Period 3 Plot 112	Broadcast Period 3 Plot 113	Broadcast Period 3 Plot 114	Injected Period 3 Plot 211	Injected Period 3 Plot 212	Injected Period 3 Plot 213	Injected Period 3 Plot 214
Broadcast Period 4 Plot 121	Broadcast Period 4 Plot 122	Broadcast Period 4 Plot 123	Broadcast Period 4 Plot 124	Injected Period 4 Plot 221	Injected Period 4 Plot 222	Injected Period 4 Plot 223	Injected Period 4 Plot 224
Broadcast Period 5 Plot 131	Broadcast Period 5 Plot 132	Broadcast Period 5 Plot 133	Broadcast Period 5 Plot 134	Injected Period 5 Plot 231	Injected Period 5 Plot 232	Injected Period 5 Plot 233	Injected Period 5 Plot 234
Broadcast Period 6 Plot 161	Broadcast Period 6 Plot 162	Broadcast Period 6 Plot 163	Broadcast Period 6 Plot 164	Injected Period 6 Plot 261	Injected Period 6 Plot 262	Injected Period 6 Plot 263	Injected Period 6 Plot 264

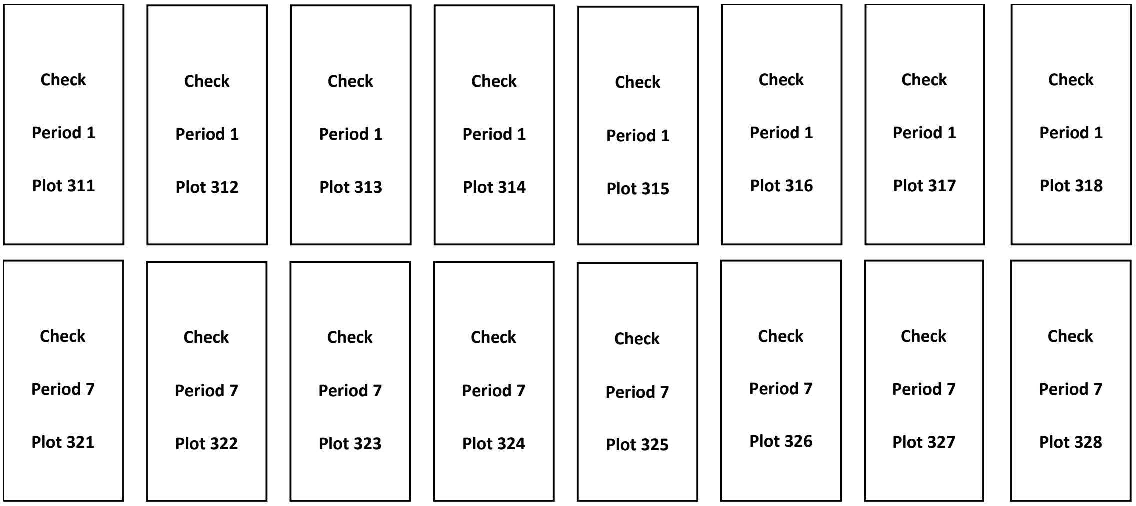
Figure 1. Schematic of plot layout and rainfall simulation period for broadcast and injected plots. Plot dimensions are not to scale.

swine slurry were obtained before application for solids and nutrient analyses, which were performed at a commercial laboratory. Mean measured values (and standard deviation) of NO_3-N, NH_4-N, TN, TP, water content, electrical conductivity (EC), and pH for the slurry were 2.4 (0.50) mg kg^{-1}, 391 (8.49) mg kg^{-1}, 5490 (112) mg kg^{-1}, 589 (33.9) mg kg^{-1}, 97% (0.71%), 42.4 (0.14) dS m^{-1}, and 8.0 (0.07), respectively.

SOIL SAMPLE COLLECTION

Information on soil nutrient values was collected to help explain differences among runoff nutrient measurements. Three soil cores were collected by hand from each plot using a 5 cm wide × 30 cm long soil probe before the rainfall simulation tests were initiated. The three cores from each plot were segmented into 0 to 10 cm, 10 to 20 cm, and 20 to 30 cm depth increments and composited. The soil samples were then air-dried, ground, and analyzed for water-soluble P (WSP), Bray and Kurtz No. 1 P (BKP), NO_3-N, NH_4-N, EC, and pH.

The Murphy and Riley (1962) method, which involved shaking 2 g of soil for 5 min with 20 mL of deionized water, was used to measure WSP. As an index of P availability, the BKP procedure (Bray and Kurtz, 1945) provides a relative estimate of P concentration in the soil solution that limits the growth of plants. Soil NO_3-N and NH_4-N concentrations (extracted using a 2 molar KCl solution) were measured with a flow injection analyzer using spectrophotometry (AutoAnalyzer 3, SEAL Analytical Ltd., Southampton, U.K.). EC and pH were determined using laboratory procedures described by Klute (1986).



Check Period 1 Plot 311	Check Period 1 Plot 312	Check Period 1 Plot 313	Check Period 1 Plot 314	Check Period 1 Plot 315	Check Period 1 Plot 316	Check Period 1 Plot 317	Check Period 1 Plot 318
Check Period 7 Plot 321	Check Period 7 Plot 322	Check Period 7 Plot 323	Check Period 7 Plot 324	Check Period 7 Plot 325	Check Period 7 Plot 326	Check Period 7 Plot 327	Check Period 7 Plot 328

Figure 2. Schematic of plot layout and rainfall simulation period for control plots. Plots dimensions are not to scale.

RAINFALL SIMULATION PROCEDURES

The initial rainfall simulation procedures adopted by the National Phosphorous Research Project included the use of three consecutive rainfall simulation runs. The application of rainfall on three consecutive days was therefore used in the present study to allow more direct comparison with results from previous studies. Current National Phosphorous Research Project rainfall simulator protocols call for application of rainfall on two consecutive days (Sharpley and Kleinman, 2003).

Rainfall was applied to paired plots at an intensity of approximately 70 mm h^{-1} for 30 min using a rainfall simulator based on the design by Humphry et al. (2002). Two additional rainfall simulation tests were conducted on the same plots at approximately 24 h intervals. The recurrence interval in this area for 105 mm of rainfall occurring over a 48 h period is approximately five years. Two rain gauges were placed along the outside perimeter of the plots, and one was placed in the center between the plots.

Water used in the study was obtained from an on-site irrigation well. Measured mean concentrations (and standard deviation) for DP (Murphy and Riley, 1962), TP (Johnson and Ulrich, 1959), NO_3-N, NH_4-N, and total nitrogen (TN) (Tate, 1994) in the irrigation water were 0.19 (0.04), 0.19 (0.04), 15.0 (1.2), 0.05 (0.04), and 15.0 (1.2) mg L^{-1}, respectively. NO_3-N and NH_4-N concentrations were measured with a flow injection analyzer using spectrophotometry (AutoAnalyzer 3, SEAL Analytical Ltd., Southampton, U.K.). The irrigation water had a mean EC of 0.75 (0.07) dS m^{-1} and a pH of 7.35 (0.07) (Klute, 1986). Concentrations of calcium, magnesium, potassium, and sodium in the irrigation water, which were measured using flame atomic adsorption spectroscopy, were 75 (6.4), 19 (0.71), 3 (0.71), and 65 (0.71) mg L^{-1}, respectively. Nutrient transport values reported in this study for DP, NO_3-N, and NH_4-N represent the difference between nutrient measurements in the runoff and those measured each day for the irrigation water.

Bormann et al. (2010) conducted a study to determine whether the source water used in simulated rainfall studies affects runoff amount, and P and sediment concentrations. Measurements of calcium, magnesium, potassium, sodium, EC, and pH of the source water used by Bormann et al. (2010) were 49 mg L^{-1}, 34 mg L^{-1}, 0.58 mg L^{-1}, 3.1 mg L^{-1}, 0.46 dS m^{-1}, and 8.3, respectively. It was found that results from simulated rainfall experiments are not likely to duplicate natural runoff composition regardless of the source of water used. Concentrations of several of the constituents used as a water source in the present study were larger than those reported by Bormann et al. (2010). Thus, results from the present investigation should only be considered to provide a relative comparison of treatment effects on runoff composition.

Plot borders channeled runoff into a sheet metal lip that emptied into a collection trough that extended along the bottom of the plots. The troughs diverted the runoff into plastic buckets where it was transferred by a sump pump into large plastic containers. Following each rainfall simulation event, the large plastic containers were weighed to determine the total mass of the runoff. The accumulated runoff was agitated immediately before sample collection to maintain suspension of solids. Runoff samples were collected for water quality and sediment analyses within a few minutes following completion of a rainfall simulation event.

Runoff samples obtained from each rainfall event were stored in plastic bottles for analyses of nutrients. The plastic bottles were kept in a cooler with ice packs until delivery at the laboratory. Plastic bottles were also used to obtain samples for sediment analysis. Total mass of the bottles used for sediment analyses was first measured. Tare weights of the bottles had been previously obtained. The plastic bottles were then dried in an oven at 105°C and weighed again to determine the mass of sediment (total solids) remaining. The sediment content of the runoff samples was determined by calculating the mass of material remaining in the bottles after drying divided by the mass of water contained in the bottles before drying (the total measured mass of liquid minus the mass of total solids). The mass of dissolved chemical constituents contained in the runoff was assumed to be negligible.

Centrifuged and filtered runoff samples of a known volume were analyzed for dissolved phosphorus (DP) (Murphy and Riley, 1962), NO_3-N, and NH_4-N (measured with a flow injection analyzer using spectrophotometry; AutoAnalyzer 3, SEAL Analytical Ltd., Southampton, U.K.). Samples that were not centrifuged were analyzed for TP (Johnson and Ulrich, 1959), TN (Tate, 1994), pH, and EC (Klute, 1986). Particulate phosphorus (PP) was obtained by subtracting DP measurements from TP values.

Addition of Inflow

Since the upslope contributing area under field conditions is much larger than that provided by the 2 m long experimental plots, additional inflow was introduced at the top of the plots to simulate longer slope lengths. Increased runoff rates resulting from longer slope lengths were simulated using previously established experimental procedures (Laflen et al., 1991; Misra et al., 1996; Monke et al., 1977). The experimental results obtained with the addition of inflow are applicable to a much larger range of rainfall and runoff conditions when nutrient transport rate is related to flow rate.

When simulated overland flow was introduced during the experimental tests, it was not practical to capture and store all of the runoff that was produced. Therefore, nutrient and sediment samples were collected under steady-state runoff conditions, and nutrient load values per unit time are reported for this portion of the study.

Water from the same well used for the rainfall simulation experiments was applied at the upgradient end of each plot after the first 30 min of the third rainfall simulation event to examine the influence of varying runoff rates on nutrient transport. Rainfall continued during the overland flow tests. Inflow was added in four successive increments to produce average runoff rates of 2.3, 6.0, 9.5, and 12.6 L min^{-1}. A mat made of a green synthetic material used as an outdoor carpet was placed beneath the inflow device to prevent scouring and create more uniform flow distribution over the plot. The remainder of the plot surface remained undisturbed.

Runoff generated during the inflow tests was transferred to a flume where a stage recorder was mounted to measure flow rate. The quantity of runoff occurring at a particular overland flow increment was only increased once the existing flow rate had achieved a steady runoff value (determined with the flume and stage recorder) and samples had been collected for nutrient and sediment analyses. Each inflow increment had a duration of approximately 8 min, which was the period of time required for steady-state flow conditions to become established and samples for nutrient and sediment analyses to be collected.

Statistical Analyses

ANOVA (SAS, 2011) was used to identify the effects of slurry application method, timing of soil collection, and soil depth on soil characteristics. The least significant difference (LSD) test was used to identify differences among experimental treatments. If a significant difference was identified, a probability level < 0.05 was considered significant.

The effects of manure application method (broadcast vs. injection) and time following slurry application (1 to 3 days, 8 to 10 days, 15 to 17 days, 22 to 24 days, and 43 to 45 days) on runoff water quality parameters were also determined by ANOVA. For a given plot, water quality measurements from each of the three rainfall simulation runs were analyzed using the Mixed procedure of SAS. The LSD test was used to identify differences among experimental treatments. If a significant difference was identified, a probability level < 0.05 was considered significant.

For the inflow test runs, ANOVA was performed to identify the effects of application method, time following slurry application, and flow rate on selected water quality parameters. ANOVA was also used to determine if changes in water quality characteristics occurred between the two rainfall simulation periods occurring on the check plots. Transformation of the soil, runoff, and inflow data to meet normality requirements was not necessary.

Results and Discussion

Soil Characteristics: Control Plots

Measurements of NO_3-N and EC increased significantly from 5.6 to 11.4 mg kg^{-1} and from 0.26 to 0.31 dS m^{-1} during the 36 days between soil sampling dates on the check plots (table 1). The change in NO_3-N concentration on the control plots can be attributed to the process of nitrogen mineralization occurring over time. The increase in soil NO_3-N content may have contributed to larger EC measurements. Eigenberg et al. (2006) reported that sequential measurement of profile-weighted soil EC could be used to identify dynamic changes in plant-available soil N. No significant differences in WSP, BKP, NH_4-N, or pH values were found between test dates on the control plots.

Values for each of the constituents except NH_4-N were significantly influenced by soil depth (table 1). The amount of NH_4-N within the soil at the time of sampling was minimal. Therefore, significant changes in NH_4-N content over time or with soil depth were not expected. Measurements of

Table 1. Soil characteristics as affected by study period and soil depth for the control plots.[a]

		WSP[b] (mg kg^{-1})	BKP[c] (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	EC[d] (dS m^{-1})	pH
Period	1	2.3	22.9	5.6 b	3.8	0.26 b	6.48
	2	1.7	18.9	11.4 a	3.3	0.31 a	6.55
Soil depth	0 to 10 cm	3.8 a	36.3 a	13.2 a	3.4	0.37 a	6.83 a
	10 to 20 cm	1.4 b	16.1 b	7.1 b	3.9	0.27 b	6.59 b
	20 to 30 cm	0.9 c	10.3 c	5.3 c	3.3	0.21 c	6.12 c
ANOVA (Pr > F)	Period	0.10	0.17	0.01	0.05	0.01	0.55
	Depth	0.01	0.01	0.01	0.17	0.01	0.01
	Period × depth	0.48	0.47	0.01	0.54	0.02	0.15

[a] Values in the same column followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

[b] WSP = water-soluble P.

[c] BKP = Bray and Kurtz No. 1 P.

[d] EC = electrical conductivity; EC and pH were determined in 1:1 soil:water ratio.

WSP, BKP, NO_3-N, EC, and pH decreased significantly with each soil depth increment.

SOIL CHARACTERISTICS: SLURRY APPLICATION PLOTS

The WSP, BKP, NO_3-N, and NH_4-N values of 2.1, 28.3, 17.1, and 7.3 mg kg^{-1} obtained on the broadcast plots were significantly greater than the measurements of 1.8, 22.1, 10.5, and 3.6 mg kg^{-1} found on the plots where slurry was injected (table 2). Manure application method did not significantly affect EC or pH values.

The length of time that elapsed following slurry application significantly affected measurements of WSP, BKP, NH_4-N, and EC (table 2). The largest values of WSP, BKP, NH_4-N, and EC occurred the first eight days following slurry application. Time following slurry application did not significantly affect NO_3-N or pH measurements.

Soil depth significantly impacted each of the soil characteristics, with values consistently decreasing as soil depth increased (table 2). Measurements of each of the soil characteristics were significantly greater at the 0 to 10 cm depth than at the other sampling increments. Values for BKP, EC, and pH were significantly less at the 20 to 30 cm depth than at the other sampling increments.

Application method by soil depth interactions were found for each of the measured soil constituents (table 2). Values for BKP and NO_3-N were significantly greater on the broadcast treatments than the injection treatments at the 0 to 10 cm depth increment (figs. 3 and 4). Differences in measurements of BKP and NO_3-N between the broadcast and injection treatments were less pronounced at the 10 to 20 and 20 to 30 cm sampling intervals.

Application method by time by soil depth interactions were identified for NH_4-N (table 2). Concentrations of NH_4-N at the 0 to 10 cm depth on the plots where slurry was broadcast were greatest initially and then steadily decreased during the first 22 days following slurry application (fig. 5). Values for NH_4-N at the 10 to 20 cm and 20 to 30 cm depth increments on the broadcast treatment were similar throughout the study. Thus, it did not appear that NH_4-N moved below the 0 to 10 cm depth on the plots where slurry was broadcast.

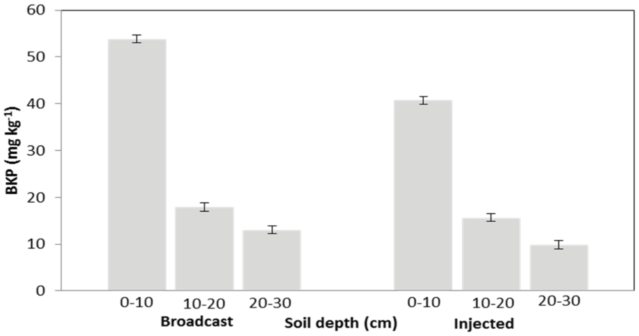


Figure 3. Bray and Kurtz No. 1 P (BKP) as affected by soil depth for the broadcast and injected experimental treatments. Vertical lines represent the standard error of the mean.

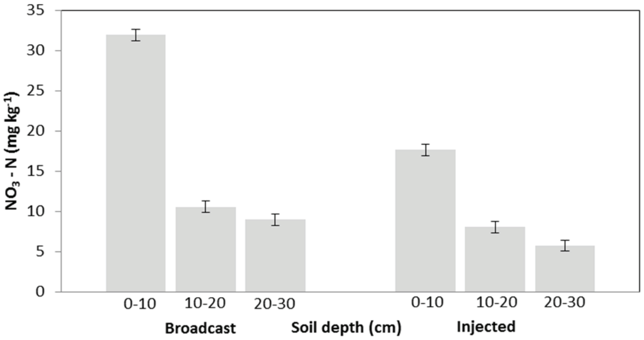


Figure 4. NO_3-N as affected by soil depth for the broadcast and injected experimental treatments. Vertical bars represent the standard error of the mean.

The mean concentration of NH_4-N on the treatments where slurry was injected was 3.6 mg kg^{-1} (table 2). A mean NH_4-N concentration of 3.6 mg kg^{-1} was also measured on the control plots where slurry was not applied (table 1). Soil samples were collected between slurry injection rows, which were spaced at 76 cm intervals. The NH_4-N contained in the slurry did not appear to have moved horizontally from the injection rows to the soil sample collection points.

Table 2. Soil characteristics as affected by application method, time since slurry application, and soil depth.[a]

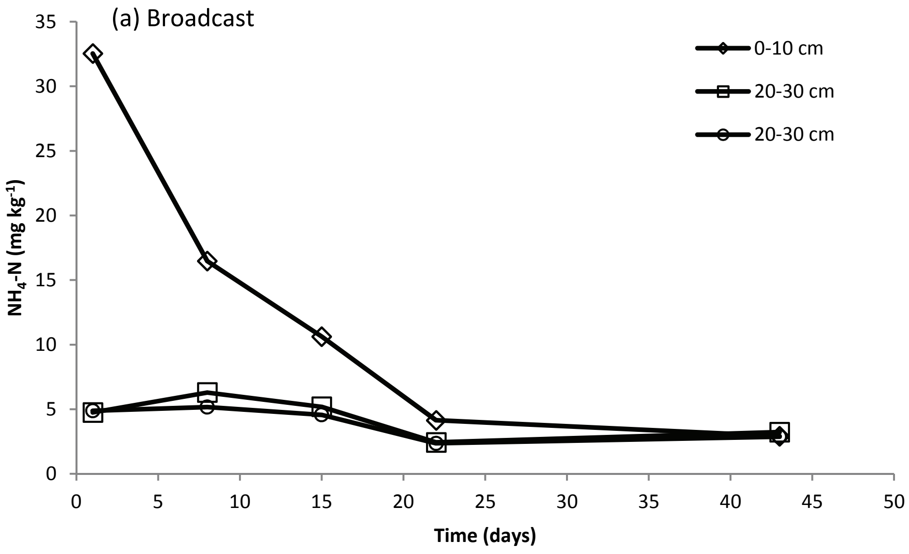
		WSP[b] (mg kg^{-1})	BKP[c] (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	EC[d] (dS m^{-1})	pH
Application method	Broadcast	2.1 a	28.3 a	17.1 a	7.3 a	0.41	6.57
	Injected	1.8 b	22.1 b	10.5 b	3.6 b	0.41	6.66
Time	1 day	1.9 b	23.6 b	9.7	8.7 a	0.35 b	6.61
	8 days	2.6 a	33.4 a	14.2	7.0 a	0.43 a	6.69
	15 days	1.8 b	23.3 b	15.1	4.9 b	0.45 a	6.66
	22 days	1.7 b	22.2 b	13.4	3.3 bc	0.40 ab	6.60
	43 days	1.7 b	23.4 b	16.8	3.0 c	0.42 a	6.52
Soil depth	0 to 10 cm	3.8 a	47.3 a	24.8 a	8.3 a	0.59 a	6.91 a
	10 to 20 cm	1.1 b	16.8 b	9.3 b	4.1 b	0.35 b	6.69 b
	20 to 30 cm	0.8 b	11.5 c	7.3 b	3.8 b	0.29 c	6.24 c
ANOVA (Pr > F)	Application	0.03	0.01	0.01	0.01	0.88	0.08
	Time	0.01	0.01	0.07	0.01	0.02	0.26
	Depth	0.01	0.01	0.01	0.01	0.01	0.01
	Application × time	0.28	0.26	0.93	0.01	0.01	0.01
	Application × depth	0.02	0.01	0.01	0.01	0.01	0.02
	Time × depth	0.12	0.73	0.17	0.01	0.08	0.13
	Application × time × depth	0.92	0.84	0.96	0.01	0.82	0.01

[a] Values in the same column followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

[b] WSP = water-soluble P.

[c] BKP = Bray and Kurtz No. 1 P.

[d] EC = electrical conductivity; EC and pH were determined in 1:1 soil: water ratio.



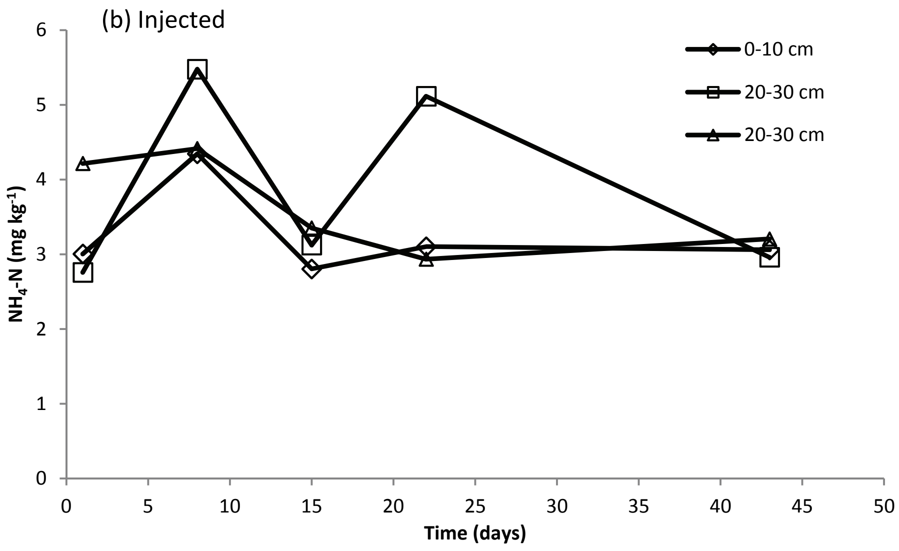


Figure 5. NH_4-N as affected by soil depth and time following slurry application for the broadcast and injected experimental treatments.

RUNOFF CHARACTERISTICS

Phosphorous Loads in Runoff

The DP load of 0.35 kg ha^{-1} measured on the broadcast treatment was significantly greater than the 0.13 kg ha^{-1} obtained for the plots on which slurry was injected (table 3). Larger runoff loads of DP were expected on the broadcast treatment since soil measurements of WSP and BKP were significantly greater on the plots where slurry was surface applied (table 2). The length of time that transpired following slurry application also significantly influenced DP loads in runoff. DP loads were reduced from a high of 0.35 kg ha^{-1} for the tests conducted 1 to 3 days after slurry application to 0.14 kg ha^{-1} for the tests performed 43 to 45 days following the addition of slurry.

Table 3. Effects of application method and time since slurry application on selected water quality parameters.[a]

		DP (kg ha^{-1})	PP (kg ha^{-1})	TP (kg ha^{-1})	NO_3-N (kg ha^{-1})	NH_4-N (kg ha^{-1})	TN (kg ha^{-1})	EC (dS m^{-1})	pH	Runoff (mm)	Soil Loss (Mg ha^{-1})
Application method	Broadcast	0.35 a	0.11 a	0.46 a	5.11	0.88	6.22	0.82 a	8.13	22	0.32b
	Injected	0.13 b	0.06 b	0.19 b	5.95	0.61	6.77	0.79 b	8.11	23	0.42a
Time	1 to 3 days	0.35 a	0.17 a	0.52 a	4.83	2.17 a	7.28	0.83	8.18 a	26	0.41a
	8 to 10 days	0.30 ab	0.11 b	0.41 a	5.85	0.84 b	7.16	0.79	8.11 b	24	0.24b
	15 to 17 days	0.22 bc	0.06 c	0.27 b	6.14	0.38 bc	6.59	0.81	8.09 b	23	0.41a
	22 to 24 days	0.19 c	0.05 c	0.23 b	5.60	0.20 c	5.81	0.80	8.10 b	21	0.46a
	43 to 45 days	0.14 c	0.04 c	0.18 b	5.25	0.14 c	5.63	0.80	8.10 b	21	0.34a
ANOVA (Pr > F)	Application	0.01	0.01	0.01	0.09	0.14	0.35	0.01	0.23	0.54	0.03
	Time	0.01	0.01	0.01	0.46	0.01	0.27	0.09	0.01	0.38	0.00
	Application × time	0.01	0.01	0.01	0.30	0.01	0.13	0.01	0.05	0.55	0.30

[a] Values are means of three rainfall simulation events conducted on consecutive days. Values in the same column followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

A significant application method by time interaction was identified for DP loads (table 3). The plots on which slurry was broadcast had larger DP loads for each interval following slurry application than the treatments on which slurry was injected (fig. 6). Variations in DP loads among sampling dates on the plots where slurry was injected were relatively small.

Loads of TP in runoff were significantly influenced by slurry application method and time following slurry addition (table 3). TP load on the broadcast treatment was 0.46 kg ha^{-1}, compared to 0.19 kg ha^{-1} on the plots where slurry was injected. Soil measurements of WSP and BKP were also significantly greater on the plots where slurry was broadcast (table 2). Loads of TP in runoff varied from a high of 0.52 kg ha^{-1} measured 1 to 3 days following slurry addition to 0.18 kg ha^{-1} obtained 43 to 45 days after the application of slurry.

A significant application method by time interaction was also determined for TP loads (table 3). TP loads on the plots where slurry was broadcast were always larger than values obtained on the treatment where slurry was injected (fig. 7). Loads of TP on the broadcast treatments declined rapidly between the 1 to 3 day and 15 to 17 day sampling intervals. Variations in TP loads among sampling dates on the plots where slurry was injected were relatively small.

Daverde et al. (2004) found that injection rather than surface application of swine slurry resulted in reductions in DRP and TP loads of 99% and 94%, respectively, when rainfall simulation tests were conducted one month and six months following slurry application. DP and TP loads in runoff measured soon after swine slurry application by Gilley et al. (2013b) decreased by 60% and 47%, respectively, when slurry was injected rather than broadcast. In the present study, injection of swine slurry reduced DP and TP loads during the 43 to 45 days following slurry addition by 63% and 59%, respectively, when compared to broadcast application.

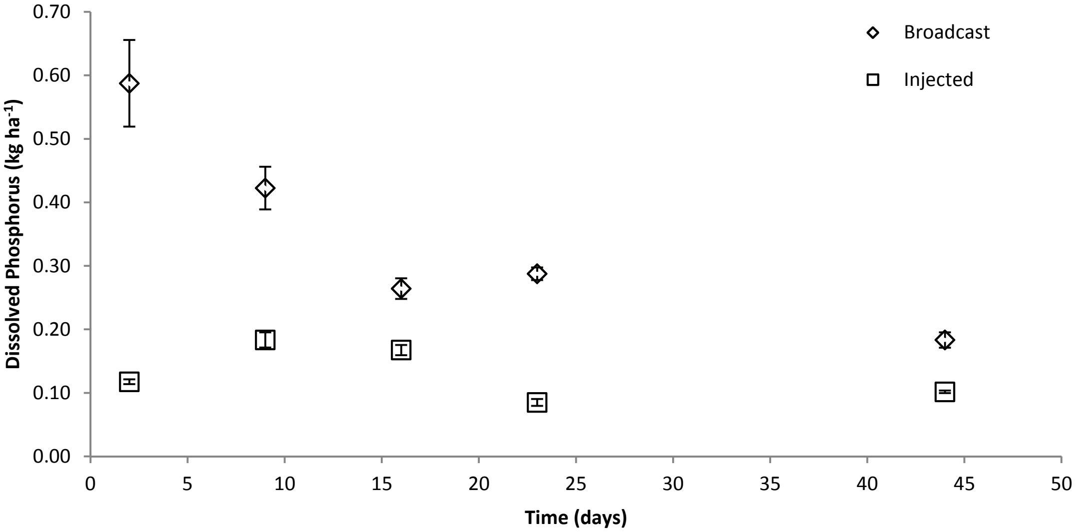


Figure 6. Dissolved phosphorus transport versus time following slurry application for the broadcast and injected experimental treatments. Vertical bars represent the standard error of the mean.

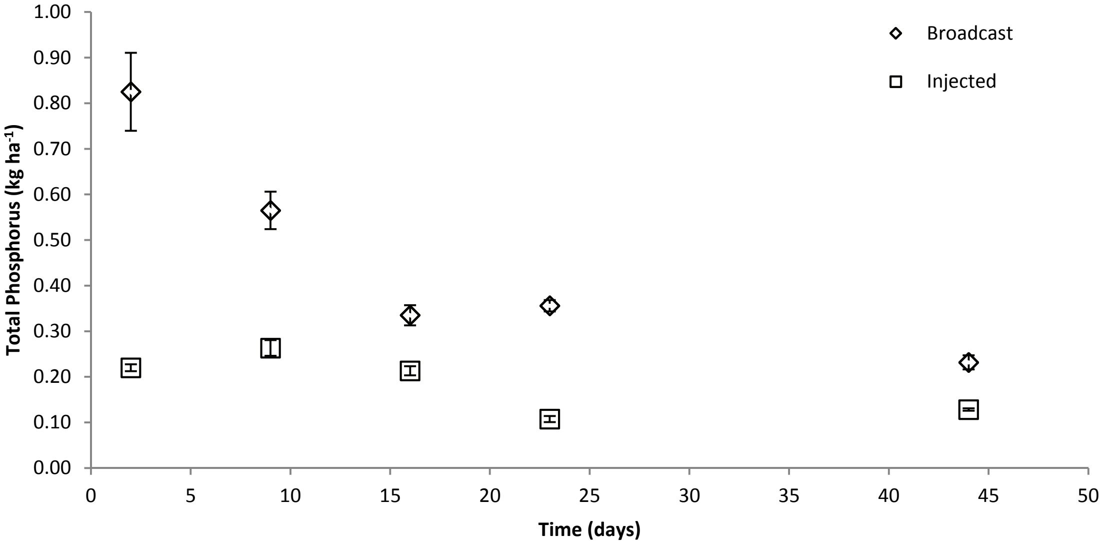


Figure 7. Total phosphorus transport versus time following slurry application for the broadcast and injected experimental treatments. Vertical bars represent the standard error of the mean.

Nitrogen Loads in Runoff

Runoff loads of NO_3-N and TN were not significantly affected by slurry application method or time following slurry addition (table 3). Application method did not significantly influence runoff loads of NH_4-N. However, NH_4-N loads were affected by the length of time following slurry application, with values decreasing from 2.17 to 0.14 kg ha^{-1} as the time following slurry application increased from 1 to 3 days to 43 to 45 days.

A significant application method by time interaction was found for NH_4-N runoff loads (table 3). NH_4-N loads on the broadcast treatment rapidly declined during the first 15 days following slurry application (fig. 8). NH_4-N is highly volatile, so the NH_4-N contained in swine slurry would be expected to rapidly dissipate following surface application. Runoff loads of NH_4-N on the plots where slurry was injected also decreased during the 15 to 17 days following slurry application, but the reductions were less dramatic. Substantial reductions in soil NH_4-N content occurred during the 15 days following slurry injection (fig. 5). Runoff loads of NH_4-N obtained 22 to 24 days and 43 to 45 days following slurry application were similar on the plots where slurry was broadcast and injected (fig. 8).

Gilley et al. (2013b) also found that application method did not significantly affect loads of NO_3-N in runoff occurring soon after swine slurry application, which was the same result found in the present investigation. The mean NO_3-N content of slurry used by Gilley et al. (2013b) was 0.7 mg kg^{-1}, and that applied in the present study was 2.4 mg kg^{-1}. Since both of these quantities are relatively small, the method by which slurry was applied would be expected to have a minimal effect on NO_3-N loads in runoff.

EC, pH, Runoff, and Soil Loss Measurements

The EC value of 0.82 dS m^{-1} obtained on the broadcast treatment was significantly greater than the 0.79 dS m^{-1} measured on the plots where slurry was injected (table 3). Many of the constituents contained in the slurry would be expected to accumulate on the soil surface following broadcast application, which would result in larger EC measurements of runoff. Time following slurry application did not significantly affect EC values.

Application method did not significantly affect pH measurements (table 3). Values for pH were significantly larger 1 to 3 days following slurry application than for the other measurement dates. Hydrogen ions are released when ammonium in the swine slurry is converted to nitrate. An increase in the concentration of hydrogen ions results in smaller pH values.

The soil loss value (0.42 Mg ha^{-1}) obtained on the plots where slurry was injected was significantly larger than the 0.32 Mg ha^{-1} measured on the broadcast treatment (table 3). Soil disturbance occurring during the slurry injection process was thought to have increased soil loss measurements. The soil loss values obtained on both the broadcast and injected treatments on this long-term no-till study site are relatively small.

RUNOFF CHARACTERISTICS AS AFFECTED BY VARYING RUNOFF RATE

Phosphorous Measurements

The transport rate for DP of 24.6 g ha^{-1} min^{-1} measured on the broadcast treatment was significantly greater than the 16.6 g ha^{-1} min^{-1} obtained for the plots on which slurry was injected (table 4). Length of time following slurry application did not significantly influence DP loads in runoff. Runoff rate significantly affected transport rates of DP, with values increasing from 10.1 to 29.8 g ha^{-1} min^{-1} as runoff rate increased from 2.3 to 12.6 L min^{-1}.

A significant application method by runoff rate interaction was identified for DP transport rates (table 4). For each runoff rate, the plots on which slurry was broadcast had larger DP transport rates than the treatments on which slurry was injected (fig. 9). The differences in transport rates between application methods became larger as runoff rates increased.

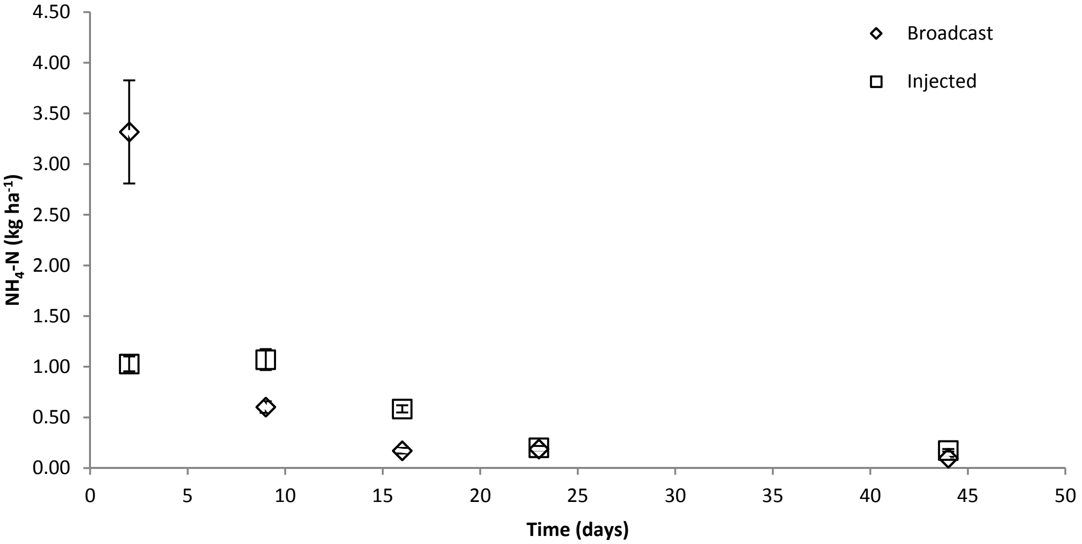


Figure 8. NH_4-N transport versus time following slurry application for the broadcast and injected experimental treatments. Vertical bars represent the standard error of the mean.

Table 4. Selected water quality parameters as affected by slurry application method, time since application, and runoff rate.[a]

	DP (g ha^{-1} min^{-1})	PP (g ha^{-1} min^{-1})	TP (g ha^{-1} min^{-1})	NO_3-N (g ha^{-1} min^{-1})	NH_4-N (g ha^{-1} min^{-1})	TN (g ha^{-1} min^{-1})	EC (dS m^{-1})	pH	Soil Loss (kg ha^{-1} min^{-1})
Application method									
Broadcast	24.6 a	5.1	29.7 a	818	19.6	902	0.71	7.88	40.3 b
Injected	16.6 b	3.9	20.5 b	869	22.3	949	0.71	7.88	59.8 a
Time									
3 days	21.3	4.7	25.9	811	39.1 a	938	0.72 a	7.97 a	51.2
10 days	25.2	7.2	32.3	979	31.3 a	1140	0.71 b	7.87 b	51.6
17 days	19.9	4.7	24.5	834	14.9 b	849	0.70 c	7.83 b	45.7
24 days	20.9	3.7	24.6	870	12.8 b	884	0.71 b	7.85 b	47.0
45 days	16.0	2.4	18.3	722	6.6 b	819	0.71 b	7.88 b	47.5
Runoff rate									
2.3 L min^{-1}	10.1 d	2.8 b	12.9 d	314 d	13.9 c	346 d	0.73 a	8.01 a	16.4 d
6.0 L min^{-1}	18.5 c	5.2 a	23.7 c	699 c	21.3 b	770 c	0.71 b	7.90 b	43.1 c
9.5 L min^{-1}	24.2 b	4.2 ab	28.4 b	1020 b	23.4 a	1130 b	0.70 c	7.82 c	59.4 b
12.6 L min^{-1}	29.8 a	5.8 a	35.5 a	1341 a	25.1 a	1460 a	0.70 c	7.79 d	75.4 a
ANOVA (Pr > F)									
Application	0.01	0.27	0.01	0.53	0.57	0.61	0.46	0.58	0.01
Time	0.24	0.08	0.11	0.39	0.01	0.21	0.01	0.01	0.93
Runoff rate	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Application × time	0.55	0.22	0.42	0.88	0.01	0.89	0.03	0.40	0.60
Application × runoff rate	0.01	0.21	0.01	0.60	0.13	0.48	0.90	0.45	0.15
Time × runoff rate	0.01	0.23	0.01	0.12	0.01	0.02	0.01	0.10	0.07
Application × time × runoff rate	0.24	0.60	0.38	0.71	0.01	0.71	0.47	0.05	0.99

[a] Values in the same column followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

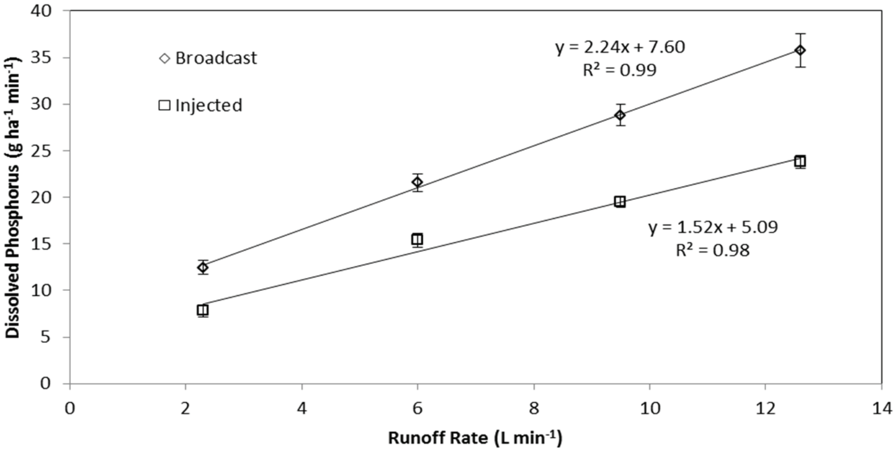


Figure 9. Dissolved phosphorus transport rate as affected by runoff rate for the broadcast and injected experimental treatments. Vertical bars represent the standard error of the mean.

Regression equations were derived relating the rate of transport of DP in runoff (y) in g ha^{-1} min^{-1} to runoff rate (x) in L min^{-1} (fig. 9).

For plots where slurry was broadcast:

$$y = 2.24x + 7.60 \quad (R^2 = 0.99) \tag{1}$$

For plots where slurry was injected:

$$y = 1.52x + 5.09 \quad (R^2 = 0.98) \tag{2}$$

Transport rates for TP were also significantly influenced by slurry application method and runoff rate (table 4). The transport rate for TP of 29.7 g ha^{-1} min^{-1} measured on the broadcast treatment was significantly greater than the 20.5 g ha^{-1} min^{-1} obtained for the plots on which slurry was injected. Rates of transport for TP increased from 12.9 to 35.5 g ha^{-1} min^{-1} as runoff rate varied from 2.3 to 12.6 L min^{-1}.

A significant application method by runoff rate interaction was identified for TP transport rates (table 4). For each runoff rate, the plots on which slurry was broadcast had larger TP transport rates than the treatments on which slurry was injected (fig. 10).

Regression equations were derived relating the rate of transport of TP in runoff (y) in g ha^{-1} min^{-1} to runoff rate (x) in L min^{-1} (fig 10).

For plots where slurry was broadcast:

$$y = 2.61x + 9.90 \quad (R^2 = 0.99) \tag{3}$$

For plots where slurry was injected:

$$y = 2.46x + 4.36 \quad (R^2 = 0.90) \tag{4}$$

Gilley et al. (2013a, 2013b) examined the effects of flow rate on runoff nutrient transport following land application of swine slurry. As was true in the present investigation, transport rates of DP, PP, and TP were found by Gilley et al. (2013a, 2013b) to increase significantly as flow rate increased.

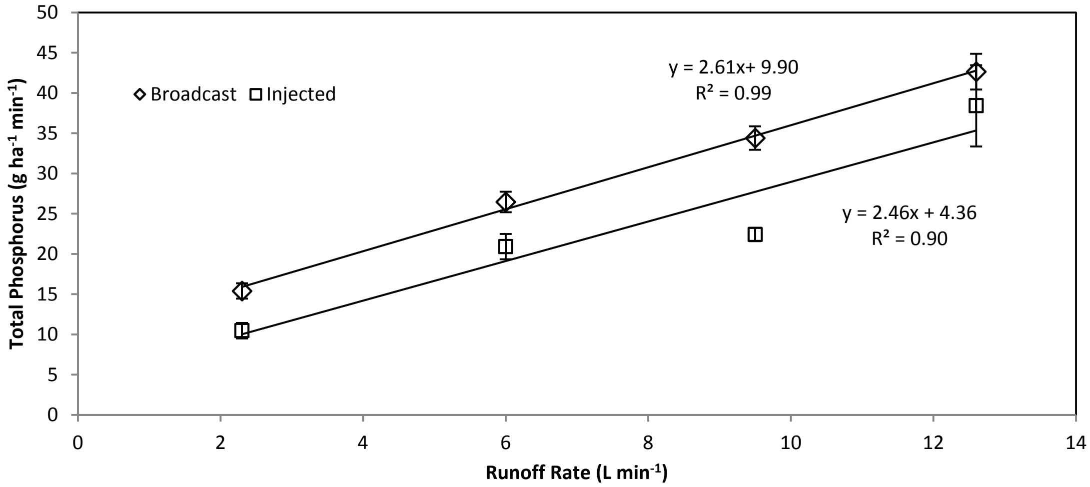


Figure 10. Total phosphorus transport rate as affected by runoff rate for the broadcast and injected experimental treatments. Vertical bars represent the standard error of the mean.

Nitrogen Measurements

Application method did not significantly affect rates of transport of NO_3-N, NH_4-N, or TN (table 4). Rates of transport of NO_3-N and TN were also not significantly influenced by time following slurry application. However, time following slurry application significantly affected NH_4-N transport rates, with measurements decreasing from 39.1 to 6.6 g ha^{-1} min^{-1} as time following slurry application increased from 3 to 45 days.

Runoff rate significantly affected transport rates of NO_3-N, NH_4-N, and TN (table 4). As runoff rate increased from 2.3 to 12.6 L min^{-1}, rates of transport of NO_3-N, NH_4-N, and TN increased from 314 to 1341 g ha^{-1} min^{-1}, from 13.9 to 25.1 g ha^{-1} min^{-1}, and from 346 to 1460 g ha^{-1} min^{-1}, respectively. Gilley et al. (2013a, 2013b) also found that rates of transport of NO_3-N, NH_4-N, and TN significantly increased as flow rates increased.

EC, pH, and Soil Loss Measurements

Measurements of EC were not significantly affected by slurry application method (table 4). EC values were found to significantly decrease from 0.72 dS m^{-1} three days following slurry application to 0.70 dS m^{-1} 17 days after slurry addition. Runoff rate also significantly influenced EC measurements, with values decreasing from 0.73 to 0.70 dS m^{-1} as runoff rate increased from 2.3 to 12.6 L min^{-1}.

Slurry application method did not significantly influence pH measurements (table 4). However, pH values decreased significantly from 7.97 to 7.88 as the period following slurry application increased from 3 to 45 days. Measurements of pH decreased significantly from 8.01 to 7.79 as runoff rate increased from 2.3 to 12.6 L min^{-1}.

The soil loss rate of 59.8 kg ha^{-1} min^{-1} measured on the injection treatment was significantly greater than the 40.3 kg ha^{-1} min^{-1} obtained on the plots where slurry was broadcast (table 4). The length of time that expired following slurry application did not significantly affect soil loss rates. Soil loss rates increased from 16.4 to 75.4 kg ha^{-1} min^{-1} as runoff rate increased from 2.3 to 12.6 L min^{-1}. The larger soil loss rates were thought to result from an increase in sediment transport capacity as flow rates became greater.

RUNOFF CHARACTERISTICS ON CONTROL PLOTS

Measurements of DP, PP, TP, and NH_4-N loads in runoff decreased by 0.02, 0.01, 0.02, and 0.01 kg ha^{-1}, respectively, during the 36-day period between simulation tests (table 5). Even though significant differences in runoff loads of DP, PP, TP, and NH_4-N were found between sampling dates, the differences were minimal. No significant differences in measurements of NO_3-N, TN, EC, or pH were found between sampling dates on the control plots. Thus, the significant differences in soil NO_3-N and EC values between sampling dates shown in table 1 did not result in corresponding significant differences in NO_3-N and EC measurements in runoff. The soil loss measurement of 0.46 Mg ha^{-1} obtained on the second sampling date was significantly greater than the 0.27 Mg ha^{-1} obtained initially (table 5). The soil loss rates measured on this long-term no-till site on both the broadcast and injection treatments were relatively small.

RUNOFF CHARACTERISTICS ON CONTROL PLOTS AS AFFECTED BY VARYING RUNOFF RATE

Timing of the rainfall simulation tests did not significantly affect measurements of DP, PP, TP, NO_3-N, TN, EC, pH, or soil loss (table 6). However, the NH_4-N transport rate of 3.4 g ha^{-1} min^{-1} measured during the initial test period was

Table 5. Effects of study period for the rainfall simulation tests on selected water quality parameters for the control plots.[a]

		DP (kg ha^{-1})	PP (kg ha^{-1})	TP (kg ha^{-1})	NO_3-N (kg ha^{-1})	NH_4-N (kg ha^{-1})	TN (kg ha^{-1})	EC (dS m^{-1})	pH	Runoff (mm)	Soil Loss (Mg ha^{-1})
Period	1	0.06 a	0.02 a	0.07 a	2.60	0.02 a	2.97	0.71	8.21	15	0.27 b
	2	0.04 b	0.01 b	0.05 b	2.51	0.01 b	2.77	0.72	8.21	14	0.46 a
ANOVA (Pr > F)	Period	0.03	0.04	0.03	0.72	0.01	0.52	0.06	0.88	0.53	0.01

[a] Values are means from three rainfall simulation events conducted on consecutive days. Values in the same column followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

Table 6. Selected water quality parameters as affected by study period for the rainfall simulation tests and runoff rate for the control plots.[a]

		DP (g ha^{-1} min^{-1})	PP (g ha^{-1} min^{-1})	TP (g ha^{-1} min^{-1})	NO_3-N (g ha^{-1} min^{-1})	NH_4-N (g ha^{-1} min^{-1})	TN (g ha^{-1} min^{-1})	EC (dS m^{-1})	pH	Soil Loss (kg ha^{-1} min^{-1})
Period	1	9.9	2.7	12.6	704	3.4 a	795	0.70	8.02	30.6
	2	12.1	1.3	13.4	754	1.4 b	811	0.70	7.91	45.1
Runoff rate	2.3 L min^{-1}	3.3 c	0.7	4.0 c	190 d	0.6 b	210 d	0.71 a	8.09 a	10.7 d
	6.0 L min^{-1}	9.0 b	2.9	11.9 b	533 c	1.5 b	584 c	0.70 b	7.98 ab	29.8 c
	9.5 L min^{-1}	14.3 a	2.1	16.4 ab	951 b	3.8 a	1046 b	0.70 b	7.91 b	48.1 b
	12.6 L min^{-1}	17.2 a	2.3	19.6 a	1242 a	3.7 a	1372 a	0.70 b	7.89 b	62.7 a
ANOVA (Pr > F)	Period	0.45	0.15	0.81	0.73	0.04	0.92	0.59	0.24	0.06
	Runoff rate	0.01	0.39	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Period × runoff rate	0.80	0.60	0.44	0.63	0.25	0.44	0.41	0.83	0.83

[a] Values in the same column followed by different letters are significantly different at the 0.05 probability level based on the LSD test.

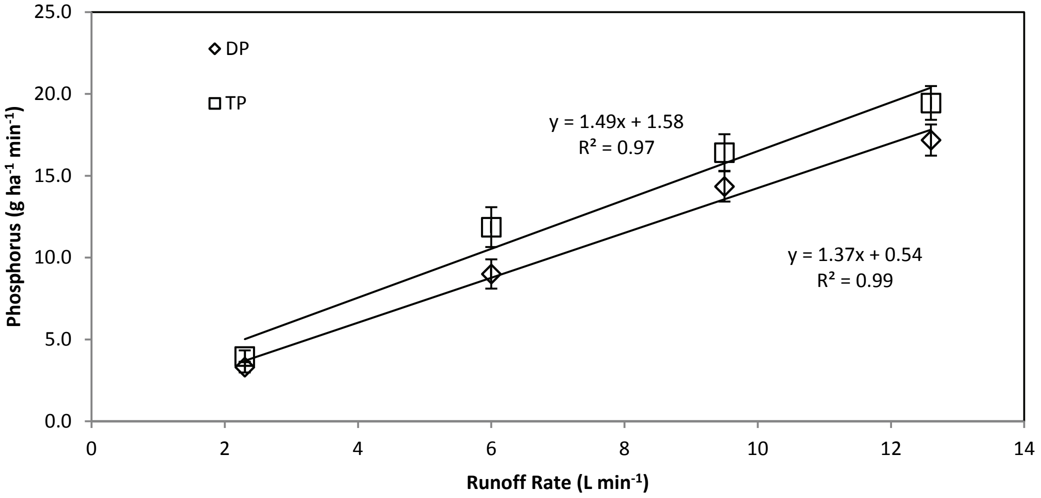


Figure 11. Dissolved phosphorus (DP) and total phosphorus (TP) transport rates as affected by runoff rate for the control plots. Vertical bars represent the standard error of the mean.

significantly greater than the 1.4 g ha^{-1} min^{-1} obtained during the second test period. The background NH_4-N content of the soil at the study site at the time of the rainfall simulation tests on the control plots was relatively small (table 1); as a result, transport rates for NH_4-N were also minimal.

Runoff rate significantly affected measurements of DP, TP, NO_3-N, NH_4-N, TN, EC, pH, and soil loss, with measurements generally increasing as flow rate increased (table 6). Regression equations were derived relating the rate of transport of DP and TP in runoff (y) in g ha^{-1} min^{-1} to runoff rate (x) in L min^{-1} (fig. 11).

Transport of DP in runoff on the control plots can be estimated from the equation:

$$y = 1.37x + 0.54 \quad (R^2 = 0.99) \tag{5}$$

Transport of TP in runoff on the control plots can be estimated from the equation:

$$y = 1.49x + 1.58 \quad (R^2 = 0.97) \tag{6}$$

Measurements of EC were reduced significantly from 0.71 to 0.70 dS m^{-1} and pH values decreased from 8.09 to 7.89 as runoff rate increased from 2.3 to 12.6 L min^{-1} (table 6).

CONCLUSIONS

This study was conducted to determine the effects of swine slurry application method, time following slurry addition, and runoff rate on runoff water quality characteristics during the first 43 to 45 days following slurry addition. Rainfall simulation tests were conducted for a 30 min duration over a three-day period at an intensity of 70 mm h^{-1}. After completion of the third rainfall simulation event, inflow was added at the top of the plots in four successive increments to simulate greater plot lengths. Runoff samples were collected for subsequent analyses of DP, PP, TP, NO_3-N, NH_4-N, TN, EC, pH, and soil loss.

The soil measurements for WSP, BKP, NO_3-N, and NH_4-N of 2.1, 28.3, 17.1, and 7.3 mg kg^{-1}, respectively, obtained on the broadcast plots were significantly greater than the values of 1.8, 22.1, 10.5, and 3.6 mg kg^{-1} found for the plots where slurry was injected. The soil disturbance resulting from slurry injection did not result in significant differences in EC and pH measurements for the long-term no-till management system examined in this study. The length of time that elapsed following slurry application significantly affected measurements of WSP, BKP, NH_4-N, and EC. Soil depth also significantly influenced each of the soil parameters, with measurements consistently decreasing as soil depth increased.

The DP and TP loads of 0.35 and 0.46 kg ha^{-1}, respectively, measured on the broadcast treatments were significantly greater than the 0.13 and 0.19 kg ha^{-1} obtained on the plots where slurry was injected. DP, TP, and NH_4-N transport loads decreased from 0.35 to 0.14 kg ha^{-1}, from 0.52 to 0.18 kg ha^{-1}, and from 2.17 to 0.14 kg ha^{-1}, respectively, as time following slurry application increased from 1 to 3 days to 43 to 45 days. For the experimental treatments where slurry was broadcast, transport loads of DP, TP, and NH_4-N decreased rapidly during the first 15 to 17 days following slurry application and then remained relatively constant. Thus, nutrient losses in runoff can be significantly reduced if slurry is broadcast when rainfall is not expected during the 15 to 17 days following application.

Runoff rate significantly affected each of the water quality parameters. Runoff loads of DP, TP, and NH_4-N increased from 10.1 to 29.8, from 12.9 to 35.5, and from 13.9 to 25.1 g ha^{-1} min^{-1}, respectively, as runoff rate increased from 2.3 to 12.6 L min^{-1}. If water quality characteristics can be related to runoff rates, it may be possible to estimate the effects of varying slope lengths and gradients, rainfall intensity and duration, and soil characteristics on pollutant loads. Permissible pollutant load is the foundation of the total maximum daily load (TMDL) process used nationwide to regulate water quality issues arising from nonpoint agricultural sources. An assessment of a producer's contribution to water quality impairment can be accomplished by estimating the water quality load of a constituent discharged during a selected period of time.

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