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Setback Distance Requirements for Removal of Swine Slurry Constituents in Runoff

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J. E. Gilley, S. L. Bartelt-Hunt, K. M. Eskridge, X. Li, A. M. Schmidt, D. D. Snow

ABSTRACT. *The use of setback distances for manure application on cropland areas adjacent to surface water bodies could serve a function similar to vegetative filter strips. However, little information currently exists to identify the setback distances necessary to effectively reduce the transport of contaminants in runoff. The objective of this study was to determine the effects of setback distance and runoff rate on concentrations of selected constituents in runoff following land application of swine slurry to a no-till cropland area in southeast Nebraska. The study site had a residue cover of 7.73 Mg ha^{-1} and a slope gradient of 4.9%. The twenty plots examined during the investigation were 3.7 m across the slope by 4.9, 7.9, 11.0, 17.1, or 23.2 m long. An initial set of rainfall simulation tests were completed to identify background concentrations of selected constituents. Swine slurry was then applied to the upper 4.9 m of each plot, and additional rainfall simulation tests were conducted on the same plots examined previously. A first-order exponential decay function was used to estimate the effects of setback distance on concentrations of selected constituents. A setback distance of 12.2 m reduced runoff concentrations of dissolved phosphorus (DP), NH_4-N, total nitrogen (TN), boron, chloride, manganese, potassium, sulfate, zinc, electrical conductivity (EC), and pH to background values similar to those measured for the no-slurry condition. Runoff rate significantly influenced transport of several of the constituents, with concentrations generally decreasing as runoff rate increased. The transport of selected pollutants in runoff was significantly reduced when setback areas were employed.*

Keywords. *Filter strips, Land application, Manure management, Manure runoff, Nitrogen, Nutrients, Phosphorus, Runoff, Swine slurry, Water quality.*

Nutrients contained in animal manures can be effectively used for crop production. Gilley and Risse (2000) assembled and summarized information quantifying the effects of manure application on runoff and soil loss from natural precipitation events and developed regression equations relating reductions in runoff and soil loss to annual manure application rates. For selected locations where manure was applied annually, runoff was reduced by 2% to 62%, and soil loss decreased by 15% to 65% compared to non-manured sites. However, if manure is applied near environmentally sensitive areas, off-site water quality impacts may arise.

A setback is an area where manure is not applied but crops continue to be grown. The transport of contaminants is reduced in setback areas by increasing the distance that overland flow must travel to reach surface water bodies. U.S. Environmental Protection Agency (EPA) requirements for concentrated animal feeding operations (CAFOs) require that manure be applied no closer than 30.5 m to any downgradient surface water, open tile intake structure, sinkhole, agricultural well head, or other conduit to surface waters (EPA, 2012). Commercial fertilizer may be added and crops grown in the setback area, and appropriate conservation practices should be implemented.

Limited information is available on the effectiveness of cropland areas as setbacks for reducing pollutants in runoff from land application areas. McDowell and Sharpley (2002) measured the fractions of P in overland flow as affected by the application of swine manure at selected upslope distances. Simulated rainfall was applied in a laboratory study to two soils from central Pennsylvania that were packed in boxes varying in length from 0.5 to 4.0 m. The concentrations of dissolved and particulate P in runoff were found to decrease with increasing flow-path length.

The effects of setback distance on concentrations of selected constituents following land application of beef cattle manure to a no-till cropland site in southeast Nebraska was examined in a field study conducted by Gilley et al. (2016). A first-order exponential decay function was used to estimate the effects of setback distance on concentration values for plot lengths varying from 4.9 to 23.2 m. A setback distance of 12.2 m effectively reduced the concentrations of dissolved phosphorus (DP), total phosphorus (TP), NH_4-N, boron, calcium, magnesium, potassium, and sulfate to back-

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ground values similar to those measured on the no-manure treatment.

The effects of setbacks on herbicide (Mickelson et al., 1998) and phosphorus (Al-wadaey et al., 2010) runoff from tile-outlet terraced fields have also been measured. The mean setback region for the study conducted by Mickelsen et al. (1998) was 11% of the drainage area, while the setback region examined by Al-wadaey et al. (2010) varied from 0% to 36% of the drainage area. The results from both studies showed that the establishment of setbacks on terraced fields with tile outlets did not reduce the transport of measured contaminants when compared to the no-setback treatments.

Where application of manure is prohibited, an 11.7 m wide vegetative buffer may be substituted as a compliance alternative to the 30.5 m setback requirement (EPA, 2012). A vegetative buffer is a permanent strip of dense perennial vegetation established parallel to the land contour and perpendicular to the predominant slope. The vegetative buffer serves to reduce the runoff rate from a land application area and enhance infiltration.

The establishment of vegetative filter strips (VFS) has been shown to substantially reduce nutrients and sediment in runoff (Dillaha et al., 1989; Magette et al., 1989; Coyne et al., 1995). The effectiveness of VFS is influenced by runoff rate, length of the vegetative filter, and characteristics of the runoff area (Bingham et al., 1980; Daniels and Gilliam, 1996; and Robinson et al., 1996).

Chaubey et al. (1995), Srivastava et al. (1996), and Lim et al. (1998) examined the effects of VFS length on the concentrations and transport of nutrients in runoff from fescue plots treated with manure. The VFS significantly reduced discharge concentrations of incoming constituents. The relationships among VFS length and discharge concentrations were well represented by first-order exponential decay functions.

The use of setback areas containing crop residue and/or actively growing vegetation where manure has not been applied could serve a function similar to VFS. Previous field experiments that examined the effectiveness of VFS in reducing the transport of constituents in incoming runoff could provide insight concerning the removal of manure constituents in runoff from cropland areas. The first-order exponential decay functions among VFS length and concentration may also have application on cropland areas. The objective of this study was to determine the effects of manure application, setback distance, and runoff rate on concentrations of selected constituents following land application of swine slurry to a no-till cropland site in southeast Nebraska.

Materials and Methods

Study Site Characteristics

This field study was conducted at the University of Nebraska Rogers Memorial Farm located 18 km east of Lincoln, Nebraska. The study site had been cropped using a long-term no-till management system with controlled wheel traffic and included winter wheat, soybeans, corn, and grain sorghum. Winter wheat was harvested from the study site in July 2015. Glyphosate was applied as needed following harvest to control weed growth. The wheat residue was not chopped or removed, and the residue provided a 100% soil surface coverage (fig. 1). The amount of vegetative material at the study site at the time of the field tests was 7.73 Mg ha^{-1}, which was typical for this no-till study site when winter wheat was grown the previous cropping season.

Runoff water quality is influenced by soil characteristics near the surface. As a result, soil samples for study site characterization were obtained at the 0 to 10 cm depth from selected locations. The soil at the site developed in loess under prairie vegetation and is considered a benchmark soil for the western Corn Belt. Using procedures for soil particle size determination reported by Kettler et al. (2001), the Aksarben clay loam (fine, smectitic, mesic Typic Argiudoll) contained 22% sand, 44% silt, and 34% clay. The saturated hydraulic conductivity of the Aksarben soil is moderately low, and the soil belongs to hydrologic group C.

Mean concentrations of Bray and Kurtz No. 1 P (Bray and Kurtz, 1945), water-soluble P (Murphy and Riley, 1962), and NO_3-N in the soil measured with a flow injection analyzer using spectrophotometry (AutoAnalyzer 3, Seal Analytical Inc., Mequon, Wisc.) were 17.9, 1.7, and 9.4 mg kg^{-1}, respectively. The study site had a mean slope gradient of 4.9%, an electrical conductivity (EC) of 0.51 dS m^{-1}, and a pH of 6.7 (Klute, 1986). Using laboratory procedures developed by Nelson and Sommers (1996), the organic matter and total carbon content of the soil were 38 and 22 g kg^{-1}, respectively, which are relatively high for cropland sites in this area. Boron, calcium, chloride, magnesium, manganese, potassium, sodium, sulfate, and zinc contents of the soil were 2.07, 3834, 2.81, 508, 12.7, 393, 24.9, 71.9, and 0.973 mg kg^{-1}, respectively.

Experimental Design

The experimental plots were established using a randomized block design with four replications (fig. 2). The nature of the rainfall simulation equipment dictated that paired plots be used. Experimental treatments included slurry application or no slurry application, setback distance, and inflow rate. The plots were 3.7 m perpendicular to the slope with lengths of 4.9, 7.9, 11.0, 17.1, or 23.2 m parallel to the slope.

Tests with slurry and with no slurry were conducted on each of the experimental plots shown in figure 2. During a weekly test regime, rainfall simulation tests on a given pair of plots were first performed with no slurry on days 1 and 2. Slurry was then applied to the upper 4.9 m of the paired plots on day 3. Additional rainfall simulation test were conducted after slurry addition on days 4 and 5 of the weekly test schedule. Field tests were performed on two plots each week during a ten-week test period (20 total plots) beginning on 23 May 2016 and ending on 5 August 2016.

Srivastava et al. (1996) examined the performance of vegetative filter strips with varying pollutant sources and filter strip lengths. They found that a manure treatment length of 3.0 m was sufficient to simulate the runoff quality associated with longer manure pollutant source areas. Recent rainfall simulation protocols require that the plots on which tests are conducted be saturated before runoff sample collection begins (Allen and Mallarino, 2008; Verbree et al., 2010). Saturation of the plots helps to minimize the effects of varying antecedent soil water conditions.

Figure 1. View of the experimental site showing wheat residue cover.

Samples for water quality analyses were collected in this investigation under steady-state runoff conditions. Many of the field experimental and analytical procedures used in this investigation for no-till cropland areas were established in studies on VFS conducted by Chaubey et al. (1995), Edwards et al. (1996), Srivastava et al. (1996), and Lim et al. (1998). Lim et al. (1998) used the following first-order exponential decay model to relate runoff concentration (C, mg L^{-1}) to VFS length (x, m):

$$C(x) = C_0 e^{-kx} \tag{1}$$

where C_0 is a coefficient, and k is a rate coefficient (with a unit of m^{-1}). Coefficient C_0 would be equal to the runoff concentration for a setback distance length of 0 m for data that are described perfectly by equation 1. However, coefficients C_0 and k were determined through regression analysis, and C_0 was not constrained to be equal to the concentration at the 0 m setback distance.

Manure Collection and Application

Swine slurry was obtained just prior to field application from a deep pit on a commercial wean-to-finish swine operation in southeast Nebraska. The slurry was collected and stored in 20 L plastic buckets until it was applied. A subsample of the slurry was obtained for chemical and physical analyses, which were performed at a commercial laboratory. Mean measured values of NO_3-N, NH_4-N, total Kjeldahl N, organic N, total phosphorus (TP), boron, calcium, magnesium, manganese, potassium, sodium, zinc, EC, pH, and solids content for the slurry were 2.43 mg kg^{-1}, 2.98 g kg^{-1}, 5.52 g kg^{-1}, 2.54 g kg^{-1}, 2.89 g kg^{-1}, 4.4 mg kg^{-1}, 2.22 g kg^{-1}, 1.95 g kg^{-1}, 43.4 mg kg^{-1}, 2.64 g kg^{-1}, 0.92 g kg^{-1}, 131 mg kg^{-1}, 25.85 dS m^{-1}, 7.81, and 5.35%, respectively. The amount of NO_3-N contained in the slurry would be expected to be minimal, since it was taken from an anaerobic pit. If total N (TN) is assumed to equal total Kjeldahl N plus NO_3-N, the fraction of TN that was soluble was 54.0%. Plant-available N (PAN) can be estimated as:

$$\text{PAN} = [NO_3\text{-N}] + (1 - NH_4\text{-N loss}) \times [NH_4\text{-N}] + \text{mineralization factor} \times [\text{organic N}] \tag{2}$$

where quantities in [brackets] are represented by mean concentrations. Loss of NH_4-N due to volitization following surface application typically ranges from 20% to 50%. Because simulated rainfall was applied in the present study soon after slurry application, a NH_4-N loss of 20% was assumed. Mineralization factors for organic nitrogen usually range from 50% to 60%, and a value of 55% was assumed for this investigation. Substituting the appropriate values into equation 2 resulted in an estimate for PAN of 3.78 g kg^{-1}. This value is similar to the estimate of 3.86 g kg^{-1} obtained using 70% of total N, as recommended by Gilbertson et al. (1979).

Slurry was applied at a rate required to meet the annual N

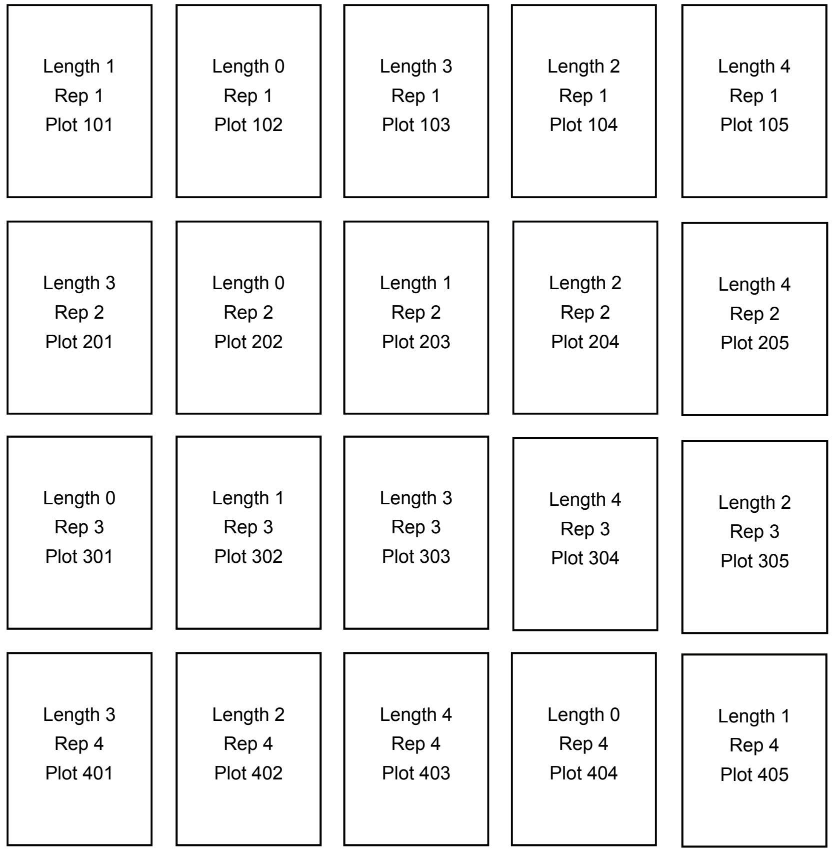

Figure 2. Schematic of the experimental plots. Plot lengths 0, 1, 2, 3, and 4 correspond to total plot lengths of 4.9, 7.9, 11.0, 17.1, and 23.2 m, respectively. Slurry was applied to the upper 4.9 m of each plot after the tests with no slurry were completed.

requirement for corn (151 kg N ha^{-1} year^{-1} for an expected yield of 9.4 Mg ha^{-1}). Soil fertility for corn was selected because its nutrient requirement was larger than that of the other crops used in the rotation. When calculating slurry application rate, it was assumed that the N availability from swine slurry was 70% of the total amount of measured N (Gilbertson et al., 1979). The slurry was applied by hand to the soil surface at a rate of 3.90×10^4 kg ha^{-1} and was not incorporated following application.

RAINFALL SIMULATION PROCEDURES

A portable rainfall simulator designed by Schulz and Yevjevich (1970) was used to apply rainfall at a rate of approximately 52 mm h^{-1} to the plots, including the setback areas (fig. 3). This is the rainfall intensity that resulted when the recommended sprinkler heads and associated equipment were used. The sprinkler head grid system used 3 m sections of 10 cm diameter irrigation pipe on which 2 cm diameter risers were mounted. Sprinkler heads were located on the top of the risers, which also contained a globe valve, a flow control valve, and a screen. The rainfall simulator was assembled in a modular fashion to accommodate plots with variable lengths. Rain gauges were placed along the outer edge of each plot to monitor rainfall intensity.

Water used in the rainfall simulation and inflow tests was obtained from an irrigation well. Measured mean concentrations of DP, total phosphorus (TP), NO_3-N, NH_4-N, and total nitrogen (TN) in the irrigation water were 0.39, 0.39, 13.0, <0.1, and 14.2 mg L^{-1}, respectively. The irrigation water had a mean EC of 0.72 dS m^{-1} and a pH of 7.5. Concentrations of boron, calcium, chloride, magnesium, manganese, potassium, sodium, sulfate, and zinc were 0.06, 83, 4, 21, 0.02, 3, 53, 15, and 0.05 mg L^{-1}, respectively.

Plot borders located along the top and sides of each plot consisted of 3 m long sections of sheet metal that diverted runoff into a collection trough. The collection trough discharged into a flume where a stage recorder was mounted to measure flow rate. Single grab samples for water quality and sediment analyses were obtained once steady-state runoff conditions were indicated by the stage recorder and flume. Runoff samples for water quality analyses were kept in a cooler containing ice packs until arrival at the laboratory.

An initial rainfall simulation run without slurry addition occurred on day 1 of the weekly test schedule at the existing soil-water state and continued until steady-state runoff conditions were established. A second rainfall simulation run was then conducted approximately 24 h later on day 2 of the weekly test period, and it also continued until steady-state runoff conditions were established. Two runoff samples for water quality analyses were obtained during each of the two simulated rainfall events. Laboratory measurements obtained from the four runoff samples were included in the statistical analyses.

Soon after completion of the second rainfall simulation run on day 2 of the weekly test period, additional field tests were conducted to identify the effects of varying runoff rates on nutrient transport. Water was added to the test plots to simulate increased runoff rates resulting from larger upslope

Figure 3. Portable rainfall simulator and paired experimental plots.

contributing areas. Rainfall continued to be applied during the inflow tests. The addition of inflow to test plots to simulate greater slope lengths is a well-established experimental procedure (Monke et al., 1977; Laflen et al., 1991; Misra et al., 1996).

A mean overland flow rate of 22.9 L min^{-1} was measured without the addition of inflow. Inflow was applied at the upgradient end of the plot while rainfall application continued at a rate of approximately 52 mm h^{-1}. Inflow was added in three successive increments to produce average runoff rates of 49.7, 63.4, and 89.8 L min^{-1}. A steady-state flow rate of 89.8 L min^{-1} would be expected for a plot approximately 90.9 m long. The two other flow rates were selected to represented intermediate values between the smallest and largest runoff values. A narrow mat made of green synthetic material often used as outdoor carpet was placed on the soil surface beneath the inflow device to prevent scouring and distribute the flow more uniformly across the plot surface.

Runoff was diverted into a flume at the bottom of the plot where a stage recorder was mounted to measure flow rate. Flow addition for each simulated overland flow increment occurred only after steady-state runoff conditions for the previous increment were reached and samples for water quality and sediment analyses had been collected. Each simulated overland flow increment was maintained for approximately 8 min. After single runoff samples for water quality and sediment analysis were obtained, the rate of inflow into the plot was increased, and additional runoff samples were collected after steady-state runoff conditions were re-established.

Slurry was applied to the upper 4.9 m of the paired plots on day 3 of the weekly test schedule. Additional rainfall simulation tests were then conducted after slurry addition on the paired plots on days 4 and 5 of the weekly test regime using the same procedures described previously. Tests with added inflow occurred on day 5.

Runoff samples were analyzed for DP after being centrifuged and filtered with filter paper having a porosity of <11 μm (Murphy and Riley, 1962). Values for DP reported in this investigation are the difference between laboratory measurements and background values obtained for the irrigation water. Samples that were not centrifuged were analyzed in a commercial laboratory for total phosphorus (TP) (Johnson and Ulrich, 1959), NO_3-N, NH_4-N, TN (Tate, 1994), boron, calcium, chloride, magnesium, manganese, potassium, sodium, sulfate, zinc, EC, and pH. The reported values represent laboratory measurements of the individual grab samples and not flow-weighted mean concentrations.

Runoff samples were also collected under steady-state conditions for sediment analysis. Tare weights of the bottles had been previously obtained. The total mass of the plastic bottles containing the runoff samples was measured. The plastic bottles were then dried in an oven at 105°C and weighed again to determine the remaining mass of sediment (total solids). 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.

Statistical Analyses

Slurry application (slurry or no slurry), setback distance (0, 3.0, 6.1, 12.2, and 18.3 m), and flow rate (22.9, 49.7, 63.4, and 89.8 L min^{-1}) were the treatment factors used in the statistical analyses. Analysis of variance was performed to determine the effects of slurry application, setback distance, and flow rate on water quality measurements (SAS, 2011). If a significant difference was identified, the least significant difference (LSD) test was used to identify differences among experimental treatments. A probability level $p \leq 0.05$ was considered significant.

Results and Discussion

Concentration Measurements

Concentration measurements for the slurry and no slurry treatments at selected setback distances are presented in table 1. Entrees for the no slurry treatment are mean concentrations obtained during the rainfall simulation tests conducted on days 1 and 2 of the weekly test schedule. Values obtained during days 4 and 5 of the weekly test schedule are reported for the slurry treatments. Measurements shown for the 0.0 setback distance in table 1 were collected at the bottom of the 4.9 m slurry application region, and they represent concentration measurements entering the setback areas.

An interaction between slurry application and setback distance was found for DP, NH_4-N, TN, boron, chloride, manganese, potassium, sodium, sulfate, zinc, and EC (table 1). No significant differences in constituent values were found among setback distances on selected treatments without slurry (figs. 4 through 7). The results shown in figures 4 through 7 for dissolved phosphorus, ammonium, potassium, and zinc are characteristic of the other constituents for which interaction effects were found. The difference between two means is not statistically significant when the standard error bars overlap. In contrast, setback distance significantly affected the concentration of constituents in runoff from the plots with slurry. A setback distance of 12.2 m reduced concentrations of DP, NH_4-N, TN, boron, chloride, manganese, potassium, sulfate, and zinc in runoff to values similar to those obtained on the no-manure treatments. As an example, concentrations of DP in runoff from the treatments containing slurry decreased from 10.15 to 0.91 mg L^{-1} as setback distance increased from 0 to 12.2 m (fig. 4). Gilley et

Table 1. Effects of slurry application and setback distance on water quality parameters averaged over two rainfall simulation runs.[a]

	DP	TP	NO_3-N	NH_4-N	TN	Boron	Ca	Cl	Mg	Mn	K	Na	Sulfate	Zinc	EC	pH	Sediment Content
Slurry application																	
No slurry	0.417 b	0.487 b	15.9	0.193 b	18.0	0.052 b	79.5	3.28 b	17.1 b	0.010	10.8 b	48.1 b	15.2 b	0.009	0.654 b	8.65 a	0.115
Slurry	4.10 a	4.85 a	14.3	5.68 a	21.1	0.077 a	78.0	14.0 a	20.8 a	0.032	20.8 a	61.8 a	17.3 a	0.029	0.794 a	8.51 b	0.123
Setback distance (m)																	
0.0	5.24 a	6.32 a	14.1	8.16 a	24.4 a	0.084 a	72.4 c	17.6 a	21.0	0.042 a	26.0 a	59.9	17.1	0.031 a	0.797 a	8.45 c	0.152
3.0	2.69 b	3.15 b	15.6	3.37 b	20.8 b	0.064 b	77.5 b	9.13 b	18.5	0.029 b	17.9 b	54.8	16.2	0.025 b	0.727 b	8.54 b	0.151
6.1	1.86 bc	2.12 b	15.3	2.08 bc	19.6 b	0.063 b	81.2 ab	8.41 b	18.9	0.015 c	14.7 b	54.2	16.4	0.017 c	0.723 b	8.61 ab	0.097
12.2	0.823 c	0.974 b	14.6	0.643 c	17.1 b	0.054 b	80.6 ab	4.28 c	18.2	0.010 c	10.1 c	53.1	15.9	0.012 d	0.686 b	8.65 a	0.093
18.3	0.683 c	0.787 b	15.8	0.419 c	18.2 b	0.057 b	82.0 a	3.69 c	18.1	0.010 c	10.3 c	52.6	15.8	0.012 d	0.688 b	8.65 a	0.103
ANOVA (p > F)																	
Slurry (S)	<0.02	0.03	0.06	0.02	0.06	0.02	0.25	<0.01	0.03	0.07	0.01	0.01	<0.01	0.06	<0.01	0.04	0.61
Length (L)	<0.01	0.01	0.56	<0.01	<0.01	<0.01	0.03	<0.01	0.29	<0.01	<0.01	0.26	0.45	0.02	0.01	0.01	0.37
S × L	<0.01	0.13	0.67	<0.01	<0.01	<0.01	0.14	<0.01	0.08	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.71

[a] All values are in mg L^{-1} except for EC (dS m^{-1}), pH, and sediment content (%). Values in the same column followed by different letters are significantly different at the 0.05 probability level based on the LSD test. DP = dissolved phosphorus, TP = total phosphorus, TN = total nitrogen, and EC = electrical conductivity.

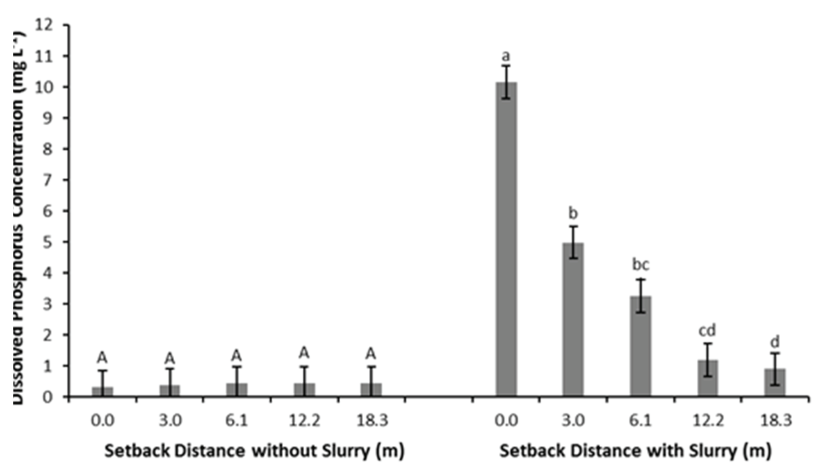

Figure 4. Dissolved phosphorus concentration as affected by setback distance with and without slurry. Vertical bars are standard errors. Values with different letters for conditions with or without slurry are significantly different at the 0.05 probability level based on the LSD test.

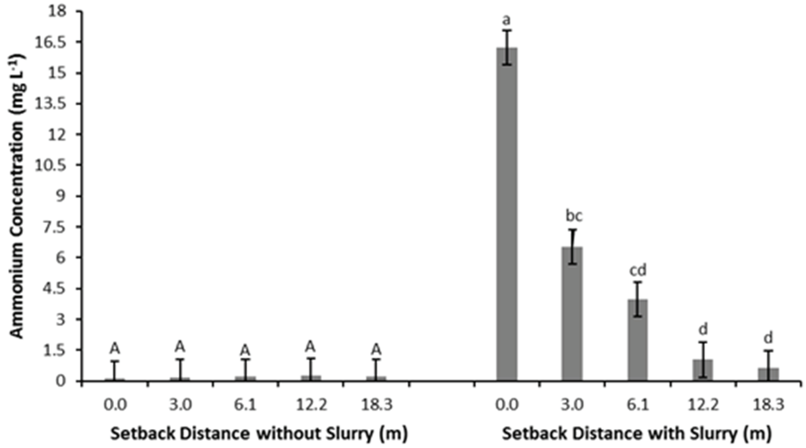

Figure 5. Ammonium concentration as affected by setback distance with and without slurry. Vertical bars are standard errors. Values with different letters for conditions with or without slurry are significantly different at the 0.05 probability level based on the LSD test.

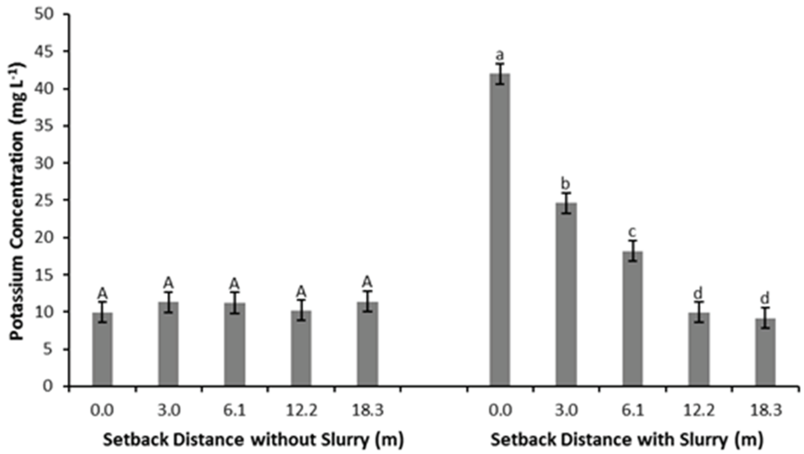

Figure 6. Potassium concentration as affected by setback distance with and without slurry. Vertical bars are standard errors. Values with different letters for conditions with or without slurry are significantly different at the 0.05 probability level based on the LSD test.

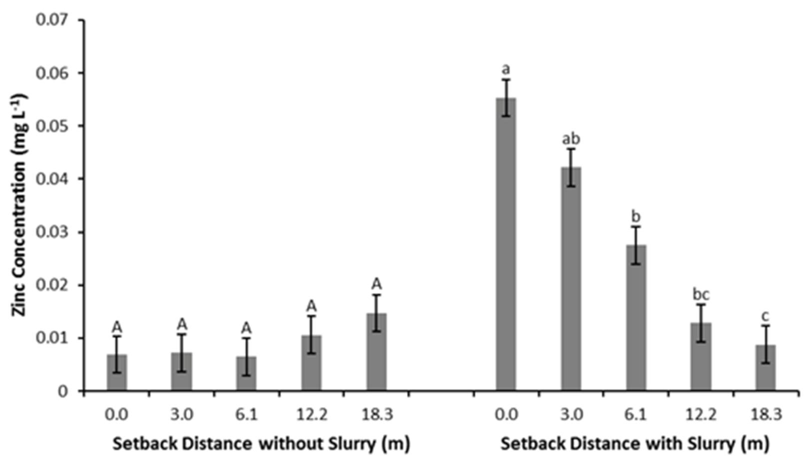

Figure 7. Zinc concentration as affected by setback distance with and without slurry. Vertical bars are standard errors. Values with different letters for conditions with or without slurry are significantly different at the 0.05 probability level based on the LSD test.

al. (2016) found that a setback distance of 12.2 m reduced concentrations of DP, TP, NH_4-N, boron, calcium, magnesium, potassium, and sulfate on plots receiving beef cattle manure to background values similar to those measured on the no-manure treatment.

The 4.85 mg L^{-1} of TP measured in runoff following slurry application was significantly greater than the 0.487 mg L^{-1} obtained for the no slurry treatment (table 1). Concentrations of TP decreased from 6.32 to 0.787 mg L^{-1} as setback distance increased from 0 to 18.3 m. No significant differences in TP concentrations were found among setback distances varying from 3.0 to 18.3 m.

The 2.43 mg L^{-1} of NO_3-N contained in the slurry was relatively low, as would be expected for slurry collected from an anaerobic pit. In comparison, the concentration of NH_4-N in slurry was 2980 mg L^{-1}. There was 9.4 mg kg^{-1} of residual NO_3-N within the upper soil profile before slurry was applied. As a result, there was no significant difference in NO_3-N concentrations of runoff between the slurry and no slurry treatments (table 1). The relatively low NO_3-N concentrations in runoff from the slurry treatments may have also been influenced by the rapid consumption of NO_3-N under anoxic conditions.

There was no significant difference in calcium concentrations in runoff between the slurry and no slurry treatments (table 1). The calcium content of the soil measured at the 0 to 10 cm depth was 3834 mg kg^{-1}, which was greater than the calcium content of the applied slurry (1950 mg kg^{-1}).

The 20.8 mg L^{-1} of magnesium measured in runoff following slurry application was significantly greater than the 17.1 mg L^{-1} obtained from the plots without slurry. No significant differences in concentrations of magnesium were found among the varying setback distances. The magnesium content of the soil measured at the 0 to 10 cm depth was 508 mg kg^{-1}, and the magnesium content of the applied slurry was 43.4 mg kg^{-1}.

A substantial surface cover was provided by the 7.73 Mg ha^{-1} of vegetative material present at the study site at the time of the rainfall simulation tests (fig. 1). A no-till management system had been established at the study location for several years. The substantial vegetative cover and no-till management system were deemed responsible for the relatively small sediment content of runoff from both the slurry and no slurry treatments (table 1).

Table 2 shows the regression coefficients and coefficients of determination (R^2) obtained when values for selected water quality constituents reported for the slurry treatments were substituted into equation 1. Table 2 reveals that the first-order exponential decay model shown in equation 1 can be used to provide estimates of setback distance following swine slurry application for many of the constituents measured in this investigation.

Chaubey et al. (1994) conducted a field study to assess the effectiveness of VFS containing fescue grass in controlling losses of sediment and nutrients from a silt loam soil treated with swine manure. The upper 3 m of the experimental plots were treated with swine manure at a rate of 200 kg N ha^{-1}. Simulated rainfall was applied at an intensity of 50 mm h^{-1} to three plots with dimensions of 1.5 m × 24.0 m until runoff had occurred for 1 h duration. Concentrations of NO_3-N, NH_3-N, total Kjeldahl nitrogen, PO_4-P, total suspended solids, and chemical oxygen demand did not decrease significantly beyond 6.0 m. A VFS length of 6.0 m reduced concentrations of NH_3-N and TP from 11.51 to 0.80 mg L^{-1} (93%) and from 11.07 to 1.18 mg L^{-1} (89%), respectively. First-order kinetics described the removal of swine manure constituents by VFS.

Table 2. First-order decay model relating the change in water quality parameter (y) to setback distance (x, m) for the plots on which slurry was applied.

Water Quality Parameter (mg L^{-1})	Equation	R^2
Dissolved phosphorus	$y = 8.07e^{-0.133x}$	0.95
Total phosphorus	$y = 9.51e^{-0.133x}$	0.95
Ammonium	$y = 12.6e^{-0.197x}$	0.96
Total nitrogen	$y = 27.6e^{-0.031x}$	0.82
Boron	$y = 0.098e^{-0.033x}$	0.72
Chloride	$y = 25.2e^{-0.107x}$	0.93
Magnesium	$y = 23.0e^{-0.013x}$	0.67
Manganese	$y = 0.058e^{-0.115x}$	0.86
Potassium	$y = 33.8e^{-0.082x}$	0.90
Sodium	$y = 67.1e^{-0.011x}$	0.76
Sulfate	$y = 18.4e^{-0.008x}$	0.81
Zinc	$y = 0.055e^{-0.106x}$	0.91
EC (dS m^{-1})	$y = 0.890e^{-0.016x}$	0.80

In the present study, swine slurry was added at a rate of 216 kg N ha^{-1} (assuming first-year N availability of 70%) to the upper 4.9 m of 3.7 × 23.2 m plots established on a site containing crop residue. Simulated rainfall was applied at a rate of 52 mm h^{-1} to a clay loam soil until steady-state runoff conditions were established. A setback distance of 6.1 m reduced concentrations of NH_4-N and TP from the treatments on which slurry was applied from 8.16 to 2.08 mg L^{-1} (75%) and from 6.32 to 2.12 mg L^{-1} (66%) (table 1), respectively.

Concentration Measurements as Affected by Inflow

Under normal field conditions, the upslope area on which manure is applied is much larger than the 4.9 m examined in this investigation. Therefore, additional flow was introduced at the top of the plots to simulate a greater upslope contributing area. Rainfall intensity and duration are both highly variable. The experimental results would be applicable to a much larger range of rainfall and runoff conditions if concentration measurements could be related to flow rate.

A three-way interaction in concentration values among slurry application, setback distance, and flow rate was found for DP, TP, NO_3-N NH_4-N, TN, boron, chloride, potassium, sodium, sulfate, zinc, and EC (table 3). Swine slurry was applied to the 4.9 m area upslope from the 0 m setback distance. As inflow was introduced at the top of the plot, the concentration of constituents at the bottom of the manure application area (0 m setback distance) decreased as a result of dilution.

The effects of varying flow rate on potassium concentration for the slurry treatments are shown in figure 8. The results obtained for potassium are characteristic of the other constituents for which three-way interactions were found. For setback distances varying from 0 to 6.1 m, concentration values for potassium, in general, decreased as flow rate increased. As an example, potassium concentration of runoff for the 0 m downslope distance decreased from 26.9 to 7.75 mg L^{-1} as flow rate increased from 22.9 to 89.8 L min^{-1}. Flow rate had a minimal effect on potassium concentration measurements at setback distances of 12.2 and 18.3 m.

An experiment to determine the effects of setback distance and runoff rate on the concentration of selected constituents following land application of beef cattle manure to a no-till cropland area was conducted by Gilley et al. (2016). At the 0 m downslope distance, potassium concentration of runoff decreased from 99.8 to 51.5 mg L^{-1} as flow rate increased from 25.6 to 87.6 L min^{-1}.

Table 3. Effects of slurry application, setback distance, and inflow on water quality parameters.[a]

	DP	TP	NO_3-N	NH_4-N	TN	Boron	Ca	Cl	Mg	Mn	K	Na	Sulfate	Zinc	EC	pH	Sediment Content
Slurry application																	
No slurry	0.325 b	0.353 b	14.0	0.095 b	15.2 b	0.0561 b	81.0 a	3.02 b	18.1 b	0.007	6.87 b	52.9 b	15.2 b	0.007 b	0.671 b	8.76 a	0.109
Slurry	2.56 a	2.94 a	14.3	3.13 a	19.3 a	0.0687 a	77.9 b	6.31 a	20.8 a	0.016	11.6 a	58.5 a	16.1 a	0.017 a	0.737 a	8.59 b	0.100
Setback distance (m)																	
0.0	1.97 a	2.32 a	14.1	3.20 a	19.3 a	0.0691	75.8 d	6.11 a	19.8	0.012	12.5 a	56.3	15.8	0.020 a	0.717	8.58 c	0.116
3.0	2.07 a	2.35 a	14.1	2.40 a	17.3 b	0.0587	78.0 c	5.15 ab	19.7	0.021	10.4 ab	55.9	15.6	0.017 a	0.710	8.65 bc	0.110
6.1	1.40 ab	1.60 b	14.2	1.33 b	17.1 b	0.0631	80.1 bc	4.52 bc	19.7	0.006	8.72 bc	55.1	15.8	0.009 b	0.699	8.69 ab	0.102
12.2	1.06 bc	1.18 bc	14.1	0.739 b	16.3 b	0.0602	81.6 a	4.03 cd	19.1	0.006	7.88 bc	55.9	15.7	0.007 b	0.696	8.70 a	0.094
18.3	0.700 c	0.795 c	14.3	0.408 bc	16.2 b	0.0609	81.6 a	3.50 d	18.9	0.012	6.83 c	55.4	15.4	0.006 b	0.697	8.75 a	0.102
Inflow																	
0	1.47	1.71	15.1 a	1.81 a	18.8 a	0.0598	79.4	6.15 a	18.6 b	0.018	12.3 a	55.9	16.4 a	0.014	0.710	8.63 b	0.111
1	1.60	1.79	14.2 ab	1.85 a	17.7 b	0.0621	78.6	4.67 bc	19.3 b	0.009	9.90 b	55.3	15.7 b	0.012	0.703	8.64 b	0.115
2	1.47	1.69	13.8 b	1.63 ab	16.8 b	0.0641	79.5	4.14 cd	19.9 a	0.008	8.29 b	55.8	15.4 b	0.010	0.702	8.69 a	0.099
3	1.23	1.40	13.6 b	1.17 b	15.7 c	0.0635	80.1	3.68 d	20.1 a	0.012	6.50 c	55.8	15.2 b	0.012	0.700	8.74 a	0.094
ANOVA																	
Slurry (S)	<0.01	<0.01	0.16	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.11	<0.01	0.01	<0.01	0.03	<0.01	<0.01	0.53
Distance (D)	<0.01	<0.01	0.99	<0.01	<0.01	0.13	<0.01	0.02	0.39	0.18	0.04	0.96	0.65	<0.01	0.30	0.01	0.93
Inflow (I)	0.06	0.07	<0.01	0.03	<0.01	0.10	0.07	<0.01	<0.01	0.26	<0.01	0.75	<0.01	0.40	0.50	<0.01	0.43
S × D	<0.01	<0.01	0.51	<0.01	<0.01	0.03	0.02	0.02	0.06	0.24	0.01	0.32	0.09	<0.01	<0.01	<0.01	0.22
S × I	0.09	0.17	0.36	0.06	0.04	0.03	<0.01	<0.01	0.53	0.44	0.06	<0.01	<0.01	0.65	<0.01	0.76	0.34
D × I	<0.01	<0.01	0.92	0.01	<0.01	<0.01	0.07	<0.01	0.34	0.02	<0.01	<0.01	0.96	0.04	0.28	0.01	0.50
S × D × I	<0.01	<0.01	0.02	0.01	<0.01	<0.01	0.44	<0.01	0.79	0.07	<0.01	0.04	0.03	<0.01	0.03	0.18	0.45

[a] All values are in mg L^{-1} except for EC (dS m^{-1}), pH, and sediment content (%). Values in the same column followed by different letters are significantly different at the 0.05 probability level based on the LSD test. DP = dissolved phosphorus, TP = total phosphorus, TN = total nitrogen, and EC = electrical conductivity.

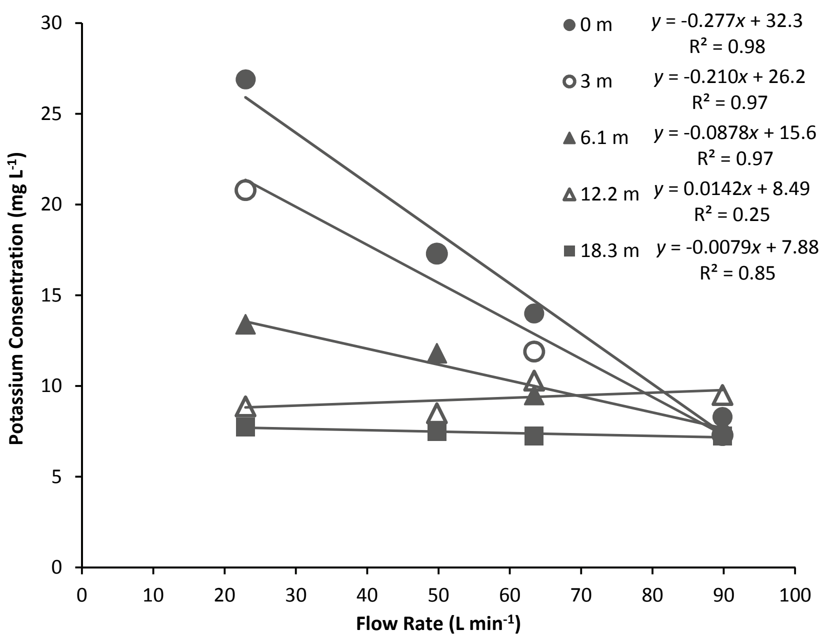

Figure 8. Potassium concentration as affected by flow rate for the slurry treatments at setback distances varying from 0.0 to 18.3 m.

CONCLUSIONS

Concentrations of DP, NH_4-N, TN, boron, chloride, manganese, potassium, sulfate, and zinc in runoff from areas on which slurry had been applied were reduced to values similar to those obtained for the no slurry treatment at a setback distance of 12.2 m. Estimates of the effects of setback distance on concentrations of selected constituents were predicted by a first-order exponential decay function. The transport of selected pollutants in runoff following land application of slurry was significantly reduced when setback distances were used.

The results obtained in this investigation are strictly applicable to the given experimental conditions. The rainfall simulation tests were performed on a no-till cropland site with a 4.9% slope gradient on which 7.73 Mg ha^{-1} of residue were present. The land application areas and flow rates occurring under field conditions are much larger than those examined in the present study. Additional experimental tests are needed to characterize the effectiveness of varying setback distances in removing pollutants in runoff from larger contributing areas with greater runoff rates, different slopes, soils, cropping, and management conditions.

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