WHEAT STRIP EFFECTS ON NUTRIENT LOADS FOLLOWING VARIABLE MANURE APPLICATIONS

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ABSTRACT. *Vegetative filters have been found to significantly reduce nutrient loads in runoff. This study was conducted to: (1) evaluate the effects of a narrow wheat strip, varying manure application rates, and different overland flow rates on runoff nutrient loads following application of beef cattle manure; (2) determine the upper capacity of a narrow wheat strip to reduce nutrient loads by applying excessive amounts of manure; and (3) compare the effectiveness of narrow wheat strips and grass hedges in reducing runoff nutrient loads. A 1.4 m wide strip of actively growing winter wheat was located at the bottom of selected 0.75 m wide by 4.0 m long plots. Three 30 min simulated rainfall events, separated by 24 h intervals, were applied at an intensity of 70 mm h^{-1} to the plots. The wheat strips were effective in reducing runoff loads of NO_3-N, NH_4-N, and total nitrogen (TN). Runoff loads of dissolved reactive phosphorus (DP), particulate phosphorus (PP), total phosphorus (TP), NH_4-N, and TN were significantly influenced by manure application rate. The application of manure to meet a 2-year rather than a 1-year corn P requirement did not significantly increase DP, PP, or TP loads. However, application of manure to meet a 4-year P requirement resulted in DP, PP, and TP loads that were significantly greater than those obtained for a 2-year P requirement. Runoff rate significantly affected each of the measured water quality parameters. The actively growing wheat strips were much less effective than grass hedges in reducing runoff nutrient loads.*

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

Placement of narrow grass hedges along the slope contour has been shown to remove sediment and dissolved solids from runoff (Dewald et al., 1996; Jin and Romkens, 2000; Kemper et al., 1992). Narrow grass hedges promote sediment deposition and berm formation, and they diffuse and spread overland flow (Dabney et al., 1995, 1999). Runoff nutrient loads are also significantly reduced by narrow grass hedges (Eghball et al., 2000; Owino et al., 2006).

Narrow grass hedges are planted at short distances along the slope contour to allow multiple passes of farm implements (Meyer et al., 1995; Dewald et al., 1996). The placement of narrow grass hedges at selected intervals along a hillslope causes much of the sediment carried by overland flow to move only a short distance before it is deposited. Sediment trapping by narrow grass hedges results primarily from upslope ponding by the hedges.

Narrow wheat strips could potentially be used to serve the same function as grass hedges in removing sediment and nutrients transported by runoff. The extensive root system provided by winter wheat would reduce erosion by helping to hold soil in place. The relatively dense vegetation would also reduce overland flow velocity, which in turn would decrease sediment transport capacity (Tollner et al., 1976, 1977). The small ponded area occurring upslope of a wheat strip may cause substantial deposition.

The incorporation of wheat strips as part of a strip cropping practice has been shown to effectively reduce soil loss from cropland areas (Gilley et al., 1997). Farmers may be more willing to incorporate an annual crop like winter wheat into their management system than to remove part of their field from crop production, as is required when narrow grass hedges are established. However, little information is currently available concerning the effectiveness of narrow wheat strips in reducing the transport of sediment and nutrients by overland flow.

Gilley et al. (2008a) conducted a field study to measure the effects of a 1.4 m wide grass hedge in reducing runoff nutrient transport from plots on which varying amounts of composted beef cattle manure was applied and incorporated several months earlier. The effectiveness of a 1.4 m wide grass hedge in reducing nutrient loads in runoff soon after varying amounts of beef cattle manure was added was examined by Gilley et al. (2011). In both studies, narrow grass hedges were found to significantly reduce runoff nutrient transport on plots where manure was applied at rates up to four times the annual N requirement for corn. The

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same experimental equipment and data collection procedures used by Gilley et al. (2008a, 2011) were employed in this investigation to allow comparison of experimental results for narrow grass hedges and wheat strips.

The results obtained by Gilley et al. (2008a, 2011) indicated that narrow grass hedges significantly reduced runoff nutrient loads for each of the manure application rates that were examined. At present, the upper capacity of grass hedges to reduce runoff nutrient loads is not known. As a result of the previous investigations on grass hedges, the objectives of the present study were expanded to include measurements of nutrient transport following excessive manure application to plots containing wheat strips.

The objectives of this study were to: (1) evaluate the effects of a narrow wheat strip, varying manure application rates, and different overland flow rates on runoff nutrient loads following application of beef cattle manure, (2) determine the upper capacity of a narrow wheat strip to reduce nutrient loads by applying excessive amounts of manure, and (3) compare the effectiveness of narrow wheat strips and grass hedges in reducing runoff nutrient loads.

Materials and Methods

Study Site Characteristics

Field tests were conducted in May and June 2010 at the University of Nebraska Roger's Memorial Farm located 18 km east of Lincoln, Nebraska, in Lancaster County. Soils at the study site were derived from loess deposits with prairie vegetation and had a mean slope of 4.8%. The top 2 cm of the Aksarben (formerly Sharpsburg) silt loam soil (fine, smectitic, mesic Typic Argiudoll) contained 17% sand, 58% silt, 25% clay, 5.3% organic matter, and 3.1% total carbon in the top 8 cm of the soil profile. The soil had an electrical conductivity (EC) of 0.31 dS m^{-1}, a pH of 7.6, and concentrations of Bray and Kurtz No. 1 phosphorus (P), water-soluble P, NO_3-N, and NH_4-N of 37.4, 2.7, 5.7, and 11.0 mg kg^{-1}, respectively. The study location had been cropped under a no-till management system using a rotation of grain sorghum (*Sorghum bicolor* (L.) Moench), soybean (*Glycine max* (L.) Merr.), and winter wheat (*Triticum aestivum* L. cv. Pastiche). Soybeans were harvested from the site before it was planted to winter wheat, and herbicide was applied as needed to control weed growth.

Plot Preparation

Twenty-four 0.75 m wide × 4 m long plots were used in this study, with the longer plot dimension parallel to the slope in the direction of overland flow. Experimental treatments included the presence or absence of a narrow wheat strip and varying manure application rate. Each of the experimental treatments was replicated three times (fig. 1).

The field site was planted to winter wheat on September 30, 2009, in a direction perpendicular to overland flow. A drill with 19 cm row spacing was used to seed winter wheat at a target population of 3.0 million seeds per hectare. Twenty-four plots were established across the slope using a randomized experimental design. Twelve plots were sprayed with a non-selective herbicide in March 2010 to kill the existing wheat plants. The same non-selective herbicide was also applied to the other 12 plots, except for a 1.4

Figure 1. Schematic showing plot layout, wheat strip and no wheat strip treatments, and manure application rates based on 0-, 1-, 2-, or 4-year corn P requirements.

Table 1. Manure analyses and application rates.

P Application Interval[a] (years)	Manure Application ($Mg\ ha^{-1}$)	NO_3-N[b] ($g\ kg^{-1}$)	NO_4-N ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	Water Content ($g\ kg^{-1}$)	EC[c] ($dS\ m^{-1}$)	pH	Total Manure N ($kg\ ha^{-1}$)	Total Fertilizer N ($kg\ ha^{-1}$)	Total P ($kg\ ha^{-1}$)
0	0	0.01	0.15	11	3.3	70	12	8.4	0	0	0
1	9	0.01	0.15	11	3.3	70	12	8.4	40	111	26
2	18	0.01	0.15	11	3.3	70	12	8.4	80	71	52
4	37	0.01	0.15	11	3.3	70	12	8.4	160	0	103
8	73	0.01	0.15	11	3.3	70	12	8.4	319	0	206
12	110	0.01	0.15	11	3.3	70	12	8.4	479	0	310
16	146	0.01	0.15	11	3.3	70	12	8.4	638	0	413
20	183	0.01	0.15	11	3.3	70	12	8.4	798	0	516

[a] Manure was applied at a rate necessary to meet a 1-, 2-, 4-, 8-, 12-, 16-, or 20-year corn P requirement.
[b] Nutrient concentration was determined on a dry basis.
[c] EC = electrical conductivity; EC and pH were determined in a 1:5 manure:water ratio.

m wide strip located on the downslope portion of the plots on which wheat continued to grow.

Substantial vegetative growth was present when the herbicide was applied. Soybean residue from the previous crops covered the soil surface at the time of the rainfall simulation tests. Field tests had been conducted previously by Gilley et al. (2008a, 2011) using 1.4 m wide switch grass (*Panicum virgatum*) hedges planted on a nearby site at the Roger's Memorial Farm. Therefore, a 1.4 m wide winter wheat strip was used in this investigation to allow comparisons with previous results.

Beef cattle manure was collected from feedlot pens located at the U.S. Meat Animal Research Center near Clay Center, Nebraska. Calves born during the spring of 2009 were placed in the pens in October 2009, and the cattle were fed a corn-based diet. Manure characteristics including TN (Bremner and Mulvaney, 1982), TP (Olsen and Sommers, 1982), and water content (Gardner, 1986) are shown in table 1.

Manure was applied uniformly to six experimental plots each week without incorporation, and the plots then remained undisturbed. Manure application rates of 0, 9.2, 18.3, or 36.6 $Mg\ ha^{-1}$ were used to meet 0-, 1-, 2-, or 4-year P-based application requirements for corn (25.8 $kg\ P\ ha^{-1}$ for an expected yield of 9.4 $Mg\ ha^{-1}$) (table 1). When calculating manure application rates, it was assumed that nitrogen (N) and P availability from beef cattle manure was 40% and 85%, respectively (Eghball et al., 2002). Supplemental urea ($(NH_2)_2CO$) fertilizer N (39-0-0, N-P-K) was added at rates required to meet annual N crop growth requirements for corn (151 $kg\ N\ ha^{-1}$ for an expected yield of 9.4 $Mg\ ha^{-1}$). Application of manure to meet the 4-year corn P requirement provided 160 $kg\ ha^{-1}$ of TN, which was slightly higher than the 151 $kg\ ha^{-1}$ annual N requirement (table 1).

Rainfall Simulation Procedures

Water used in the rainfall simulation tests was obtained from an irrigation well. Reported nutrient values represent the difference between runoff measurements and concentrations in the irrigation well water. Measured mean concentrations of DP, TP, NO_3-N, NH_4-N, and TN in the irrigation water were 0.17, 0.17, 14.9, 0.00, and 14.9 $mg\ L^{-1}$, respectively. The irrigation water had an EC of 0.79 $dS\ m^{-1}$ and a pH of 7.4.

Rainfall simulation procedures adopted by the National Phosphorus Research Project (Sharpley and Kleinman, 2003) were employed in this study, which occurred from May 25 to June 19, 2010. A portable rainfall simulator based on the design by Humphry et al. (2002) was used to apply rainfall for 30 min at an intensity of 70 $mm\ h^{-1}$. A storm in this area with this intensity and duration has approximately a 5-year recurrence interval (Hershfield, 1961). Two additional rainfall simulation tests were conducted for the same duration and intensity at approximately 24 h intervals. Four rain gauges were placed along the outer edge of each plot, and two rain gauges were located between the plots. The area disturbed by placement of the sheet metal borders around the perimeter of the plot was relatively small, thus reducing the potential for preferential infiltration.

Water was slowly added to the plots using a garden hose with an adjustable nozzle until runoff was first observed. The addition of water before the rainfall simulation tests helped to provide more uniform antecedent soil water conditions among the experimental treatments. Under actual field conditions, antecedent soil water conditions vary substantially depending on the time of year and previous precipitation.

Plot borders channeled runoff into a sheet metal lip that emptied into a collection trough located across the bottom

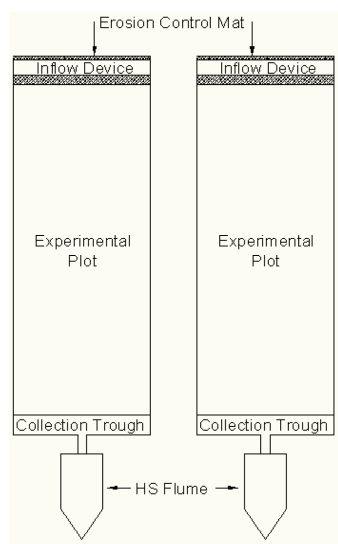

Figure 2. Schematic showing a pair of experimental plots, inflow devices, collection troughs, and HS flumes used in this study.

of each plot that diverted runoff into plastic buckets (fig. 2). A sump pump was then used to transfer runoff into larger plastic storage containers. The storage containers were weighed at the completion of each run to determine total runoff volume. Accumulated runoff was agitated to maintain suspension of solids. A runoff sample was collected for water quality analysis, and an additional sample was obtained for sediment analysis.

Centrifuged and filtered runoff samples were analyzed for DP (Murphy and Riley, 1962) and NO_3-N and NH_4-N using a Lachat system (Zellweger Analytics, Milwaukee, Wisc.). Non-centrifuged samples were analyzed for TP (Johnson and Ulrich, 1959, pp. 26-78), TN (Tate, 1994), pH, and EC. The samples obtained for sediment analysis were dried in an oven at 105°C and then weighed to determine sediment content.

Simulated overland flow was applied at the upgradient end of each plot after the first 30 min of the third rainfall event. The simulated overland flow tests did not begin until each of the three 30 min simulated rainfall applications that occurred on three consecutive days had been completed. The added inflow was used to simulate the movement of overland flow into the test section from upslope areas, not the occurrence of rainfall with a high recurrence interval onto the plot surface.

Inflow was added in four successive increments to produce average runoff rates of 4.3, 9.8, 14.2, and 22.6 L min^{-1} on the plots with a wheat strip and 4.6, 10.1, 15.2, and 23.1 L min^{-1} on the plots without a wheat strip. A 2.5 cm diameter plastic tube that extended across the top of the plot served as an inflow device. Several holes were drilled into the plastic tube to allow water to be introduced uniformly across the plot surface. A gate valve and pressure gauge located on the inflow device were adjusted to provide the desired flow rate.

The addition of inflow to the test plots to simulate greater slope length is a well established experimental procedure (Monke et al., 1977; Laflen et al., 1991). A mean overland flow rate of 2.3 L min^{-1} was measured without the addition of simulated overland flow. The largest mean overland flow rate was 22.9 L min^{-1}, or approximately 10 times the rate obtained without the addition of inflow. The use of runoff quantities substantially larger than 22.9 L min^{-1} did not seem reasonable for the size of the plots used in this study. Three additional intermediate simulated overland flow quantities were selected to provide overland flow rates useful for comparison. Using runoff measurements without the addition of rainfall as a reference, simulated plots lengths were approximately 7.7, 17.2, 25.6, and 39.8 m.

A mat consisting of material typically used for outdoor carpet was placed on the soil surface beneath the inflow device to prevent scouring and distribute flow more uniformly across the plot surface (fig. 2). Flow addition for each inflow increment usually occurred for approximately 8 min. This was the period of time typically required for steady runoff conditions to become established, as indicated by stage recorder measurements, and samples for sediment and nutrient analyses to be collected. Rainfall continued during the simulated overland flow tests.

Runoff was diverted into a flume on which a stage recorder was mounted to measure flow rate. Flow addition for each simulated overland flow increment occurred only after steady runoff conditions for the previous increment was reached and samples for nutrient and sediment analyses had been collected. Steady runoff conditions were determined from visual observations of the stage recorder.

Tests with Excessive Manure Application

Additional tests were conducted to measure the upper capacity of wheat strips to reduce nutrient loads following excessive manure application. The day following completion of the third rainfall simulation run and inflow tests, additional manure was added to the 12 plots containing a wheat strip to provide total manure application rates of 73.2, 109.8, 146.4, or 183.0 Mg ha^{-1}, which correspond to 8-, 12-, 16-, or 20-year corn P requirements (table 1). Each of the four excessive manure application rates was replicated three times. The desired manure application rate was reduced by the amount of manure that had been previously applied. A fourth rainfall simulation test was then conducted for 30 min. Inflow was again added to the top of the plots in four successive increments, with rainfall continuing during the inflow tests, to produce average runoff rates of 4.7, 9.8, 14.4, and 22.0 L min^{-1}. The data collection procedures that were employed previously were used for the tests conducted following excessive manure application.

Statistical Analyses

The effects of a wheat strip, manure application rate, and flow rate on runoff nutrient loads were determined using analysis of variance (ANOVA) (SAS, 2003). For a given plot, water quality measurements obtained from each of the three rainfall simulation runs were included in the analyses and were treated as repeated measures. By using ANOVA, it was possible to test for significant differences among experimental variables. If a significant difference was identified, the least significant difference test (LSD) was used to identify differences among experimental variables. Student's t test was used to identify significant differences among experimental variables for the plots on which excessive amounts of manure were applied. A probability level <0.05 was considered significant.

Results and Discussion

Water Quality Characteristics of Runoff

Significant wheat strip by manure application rate interactions were found for EC (table 2). The wheat strip significantly influenced measurements of DP, NO_3-N, NH_4-N, TN, and EC. However, measurements of PP, TP, pH, runoff, and erosion were not significantly influenced by the wheat strip. The wheat strip was expected to reduce sediment transport and correspondingly decrease PP and TP loads in runoff. However, a substantial amount of crop residue was present on the study site due to the long-term no-till practices used on the farm. As a result, measurements of runoff, erosion, PP load, and TP load were similar on the plots with and without a wheat strip.

Table 2. Effects of wheat strip and manure application rate on selected water quality parameters averaged over three rainfall simulation runs.[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)	Erosion ($Mg\ ha^{-1}$)
Wheat strip										
Wheat strip	0.07 b	0.13	0.20	0.09 b	0.10 b	1.03 b	0.83 b	7.9	22	0.14
No-wheat strip	0.11 a	0.15	0.26	0.20 a	0.21 a	2.12 a	0.89 a	7.9	22	0.18
Manure rate ($Mg\ ha^{-1}$)										
0	0.03 c	0.10 b	0.13 b	0.15	0.01 c	0.41 b	0.78 c	7.9	26	0.16
9.2	0.07 bc	0.11 b	0.18 b	0.19	0.27 a	2.72 a	0.81 c	7.9	24	0.17
18.3	0.10 b	0.12 b	0.22 b	0.15	0.21 a	2.14 a	0.88 b	7.9	20	0.13
36.6	0.18 a	0.22 a	0.40 a	0.09	0.14 b	1.03 b	0.97 a	7.9	20	0.18
ANOVA (Pr > F)										
Wheat strip	0.02	0.34	0.12	0.04	0.01	0.01	0.01	0.29	0.96	0.17
Manure rate	0.01	0.02	0.01	0.61	0.01	0.01	0.01	0.92	0.38	0.49
Wheat strip × manure rate	0.06	0.34	0.17	0.54	0.13	0.31	0.01	0.41	0.77	0.85

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

Manure application rate significantly affected measurements of DP, PP, TP, NH_4-N, TN, and EC. However, measurements of NO_3-N, pH, runoff, and erosion were not significantly influenced by the quantity of manure that was applied. The amount of NO_3-N contained in the manure at the time of application was relatively small; therefore, NO_3-N loads in runoff were also small.

Phosphorus Measurements

The wheat strip reduced the DP load in runoff from 0.11 to 0.07 kg ha^{-1}, or 36% (table 2). The decrease in DP load on the plots with a wheat strip was influenced by the reduction in upslope contributing area of 35% provided by the 1.4 m wide wheat strip. Thus, it appears that the principal benefit provided by the wheat strip in reducing DP loads in runoff was a smaller upslope contributing area.

The load of DP in runoff increased from 0.03 to 0.18 kg ha^{-1} as manure application rate increased from 0 to 36.6 Mg ha^{-1}. The application of manure to meet a 2-year rather than a 1-year corn P requirement did not significantly increase the DP load. However, application of manure to meet a 4-year P requirement resulted in a DP load that was significantly greater than that obtained for a 2-year P requirement. Regression equations were derived relating DP load (y) in kg ha^{-1} to manure application rate (x) in Mg ha^{-1}:

For the treatments containing a wheat strip:

$$y = 0.0022x + 0.035 \quad (R^2 = 0.94)$$

For the treatments with no wheat strip:

$$y = 0.0059x + 0.019 \quad (R^2 = 0.99)$$

The PP and TP loads in runoff were not significantly affected by the wheat strip. As the manure application rate increased from 0 to 36.6 Mg ha^{-1}, the load of PP and TP in runoff increased from 0.10 to 0.22 kg ha^{-1} and from 0.13 to 0.40 kg ha^{-1}, respectively (table 2). No significant differences in PP or TP load were found between plots where manure was applied to meet 1- or 2-year corn P requirements. However, the PP and TP loads in runoff were significantly greater on the plots where manure was applied to meet a 4-year compared to a 2-year P requirement. A regression equation was derived relating TP load (y) in kg ha^{-1} to manure application rate (x) in Mg ha^{-1}:

$$y = 0.0074x + 0.11 \quad (R^2 = 0.97)$$

The effects of a 0.75 m wide switch grass hedge on the transport of nutrients following application of beef cattle manure to meet a 1-year N requirement for corn was examined by Eghball et al. (2000). The hedge was located at the bottom of 10.7 m long plots established on a Monona silt loam soil positioned on a 12% slope in southwest Iowa. Two 1 h simulated rainfall events separated by 24 h were applied to the experimental plots. The grass hedges reduced concentrations of DP, PP, and TP during the wet rainfall simulation event by 47%, 38%, and 40%, respectively. Thus, the narrow grass hedges examined by Eghball et al. (2000) were much more effective in reducing P transport than the narrow wheat strips examined in this study.

Nitrogen Measurements

The mean runoff loads of NO_3-N, NH_4-N, and TN on the plots without a wheat strip were 0.20, 0.21, and 2.12 kg ha^{-1}, respectively, which were significantly larger than the values of 0.09, 0.10, and 1.03 kg ha^{-1} measured on the plots with wheat strips (table 2). Runoff NO_3-N load was not significantly affected by manure application rate because of the small amount of NO_3-N contained in manure (table 1). Runoff loads of NH_4-N and TN varied from 0.01 to 0.27 kg ha^{-1} and from 0.41 to 2.72 kg ha^{-1}, respectively (table 2). It is not know why the measured loads of NH_4-N and TN in runoff were smaller for the manure application rate of 36.6 Mg ha^{-1} than for the other application rates.

Eghball et al. (2000) also measured NH_4-N concentrations of runoff as affected by a narrow grass hedge. The switch grass hedge reduced NH_4-N concentrations by 60%, which was slightly larger than the 52% reduction in NH_4-N concentration measured in the present investigation.

The amount of N and P in cattle manure available the first year after application has been estimated as 40% and 85%, respectively (Eghball et al., 2002). This study was conducted to measure nutrient loads in runoff occurring immediately after manure application. Additional testing will be necessary to identify the effects of mineralization of organic nutrients in manure on runoff nutrient loads.

EC, pH, Runoff, and Erosion Measurements

EC was significantly larger on the plots without a wheat strip than on the plots with a wheat strip, with values measured as 0.89 and 0.83 dS m^{-1}, respectively (table 2). Wheat residue has been found to absorb nutrients contained in solution (Cermak et al., 2004; Gilley et al., 2009). It is possible that vegetative materials contained in the wheat strip

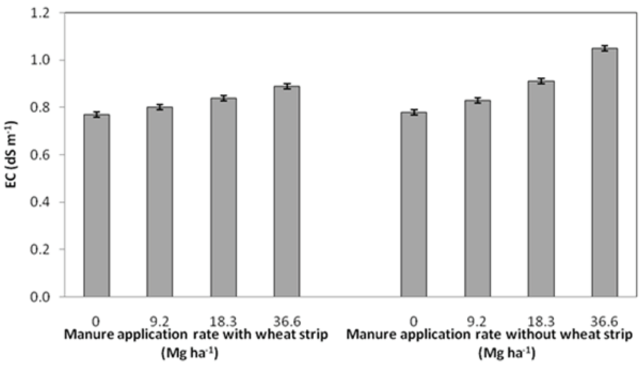

Figure 3. Electrical conductivity (EC) as affected by manure application rate for the wheat strip and no wheat strip treatments. Vertical bars are standard errors.

adsorbed chemical constituents present in runoff, thus reducing EC values.

Measurements of EC increased significantly from 0.78 to 0.97 dS m^{-1} as manure application rate increased from 0 to 36.6 Mg ha^{-1}. The soluble salts contained in manure are readily transported by overland flow. The application of increased amounts of manure provided additional chemical constituents available for transport by overland flow.

The EC values increased with manure application rate on the plots both with and without a wheat strip (fig. 3). The wheat strip significantly reduced EC measurements for the two largest manure application rates of 18.3 and 36.6 Mg ha^{-1}. Regression equations were derived relating EC (y) in dS m^{-1} to manure application rate (x) in Mg ha^{-1}:

For the treatments containing a wheat strip:

$$y = 0.0033x + 0.77 \quad (R^2 = 0.99)$$

For the treatments with no wheat strip:

$$y = 0.0075x + 0.77 \quad (R^2 = 0.99)$$

The mean pH value of 7.9 was not significantly affected by the wheat strip or manure application rate. Water was added to the plot surfaces before initiation of rainfall to maintain uniform antecedent soil water conditions. As a result, the mean quantity of runoff of 22 mm was not significantly affected by the wheat strip or manure application rate.

Mean erosion for the experimental tests was 0.16 Mg ha^{-1}. Erosion measurements were not significantly affected by the wheat strip or manure application rate. The study site had been cropped for several years using a no-till management system, so minimal erosion occurs at this location. The presence of the narrow wheat strip did not significantly reduce measured soil loss values for the existing experimental conditions.

Gilley et al. (1997) measured soil loss from 3.0 m wide × 11.7 m long plots during two 1 h rainfall simulation events conducted at an intensity of 64 mm h^{-1}. Some of the plots contained a 3.9 m long strip of actively growing winter wheat planted perpendicular to the direction of overland flow and located below a 7.8 m long strip with no residue that had been recently tilled. Other plots contained an 11.7 m long strip with no residue that also had been recently tilled. Total soil loss on the plots with the winter wheat strip was 5.1 Mg ha^{-1}, a reduction of 93% from the 74.7 Mg ha^{-1} measured from the plots with no residue.

In the present study, mean erosion was 0.16 Mg ha^{-1}, a fraction of the amount measured in the study conducted by Gilley et al. (1997). A strip of actively growing winter wheat would be expected to be much more effective in reducing soil loss when relatively large amounts of sediment are transported by overland flow. A long-term no-till crop management system had been established on the farm used in this study. As a result, erosion measurements were very small on the plots with and without a wheat strip.

Water Quality Characteristics as Affected by Runoff Rate

Significant wheat strip by runoff rate interactions were found for DP when inflow was added (table 3). A significant manure application rate by runoff rate interaction was found for EC. The wheat strip significantly reduced measurements of DP and TP. Manure application rate significantly affected measurements of DP, TP, NO_3-N, NH_4-N, and EC. Each of the measured water quality parameters was significantly influenced by runoff rate.

Phosphorus Measurements

The mean transport rate for DP resulting from inflow on the plots with a wheat strip was 42% less than for the plots without a wheat strip, with values measured as 2.6 and 4.5 g ha^{-1} min^{-1}, respectively (table 3). The 42% reduction in DP transport rate was slightly larger than the 35% reduction in upslope contributing area on the plots containing the 1.4 m wide wheat strip. The transport rate for DP consistently increased with each increase in flow rate on the plots without a wheat strip (fig. 4). The transport rate for DP was less on the plots with a wheat strip than without a wheat strip for each of the inflow increments, with the differences most pronounced at the largest runoff rates. Regression equations were derived relating rate of DP transport (y) in g ha^{-1} min^{-1} to runoff rate (x) in L min^{-1}:

For the treatments containing a wheat strip:

$$y = 0.11x + 1.51 \quad (R^2 = 0.88)$$

For the treatments with no wheat strip:

$$y = 0.20x + 2.30 \quad (R^2 = 0.97)$$

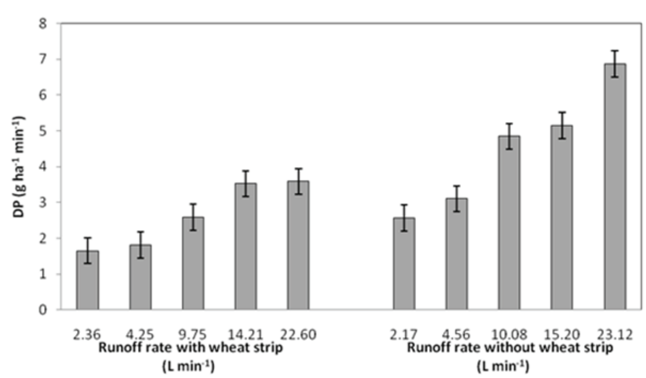

Figure 4. Runoff loads for dissolved phosphorus (DP) as affected by runoff rate for conditions with and without a wheat strip. Vertical bars are standard errors.

Table 3. Runoff water quality parameters as affected by a wheat strip, manure application rate, and runoff rate.[a]

	DP ($g\ ha^{-1}\ min^{-1}$)	PP ($g\ ha^{-1}$)	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 ($kg\ ha^{-1}\ min^{-1}$)
Wheat strip									
Wheat strip	2.6 b	10.0	12.6 b	5.0	4.3	82	0.79	7.7	18
No-wheat strip	4.5 a	11.2	15.7 a	5.3	5.1	80	0.79	7.8	20
Manure rate ($Mg\ ha^{-1}$)									
0	1.8 c	11.0	12.8 b	3.9 b	0.9 c	58	0.78 b	7.7	19
9.2	2.2 bc	10.0	12.2 b	8.4 a	8.8 a	85	0.79 b	7.8	20
18.3	3.8 b	7.9	11.6 b	4.6 b	5.4 b	85	0.79 b	7.8	16
36.6	6.5 a	13.5	20.0 a	3.6 b	3.7 b	96	0.80 a	7.8	20
Runoff rate ($L\ min^{-1}$)									
2.3	2.1 c	3.6 d	5.8 d	3.7 bc	4.8 ab	26 c	0.80 a	8.0 a	5 d
4.4	2.5 c	4.9 d	7.4 d	1.7 c	3.6 b	35 bc	0.79 b	7.8 b	8 d
9.9	3.7 b	9.1 c	12.8 c	5.3 b	5.8 a	81 b	0.79 b	7.7 c	18 c
14.7	4.3 b	13.4 b	17.8 b	6.0 ab	5.9 a	138 a	0.78 c	7.7 c	24 b
22.9	5.2 a	22.0 a	27.2 a	9.0 a	3.5 b	127 a	0.78 c	7.6 d	40 a
ANOVA (Pr > F)									
Wheat strip	0.02	0.43	0.04	0.79	0.33	0.89	0.72	0.49	0.38
Manure rate	0.01	0.12	0.01	0.01	0.01	0.49	0.04	0.97	0.67
Runoff rate	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
Wheat strip × manure rate	0.11	0.60	0.13	0.17	0.14	0.14	0.56	0.57	0.30
Wheat strip × runoff rate	0.02	0.85	0.43	0.66	0.36	0.96	0.08	0.58	0.58
Manure rate × runoff rate	0.10	0.48	0.30	0.88	0.31	0.34	0.01	0.88	0.99
Wheat strip × manure rate × runoff rate	0.51	0.96	0.80	0.14	0.54	0.77	0.07	0.99	0.06

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

The presence of a wheat strip and manure application rate did not significantly affect transport rates for PP when inflow was added (table 3). There was a substantial amount of crop residue at the study site, since no-till farming practices are used on the farm. As a result, no significant differences in soil loss rate or PP transport rate were found between the wheat strip and no wheat strip treatments. However, transport rates for PP were significantly influenced by runoff rate, with measured values increasing from 3.6 to 22.0 $g\ ha^{-1}\ min^{-1}$ as runoff rate increased from 2.3 to 22.9 $L\ min^{-1}$. Significant differences in transport rates for PP were found among each of the runoff rates varying from 4.4 to 22.9 $L\ min^{-1}$.

The mean transport rate for TP on the plots with and without wheat strips was 12.6 and 15.7 $g\ ha^{-1}\ min^{-1}$, respectively, which was a reduction of 20% (table 3). The upslope contributing area was 35% less on the plots containing the 1.4 m wide wheat strip. Thus, it does not appear that the wheat strip provided a benefit in reducing TP transport rates in addition to providing a smaller upslope contributing area. Runoff rate significantly affected transport rates for TP, with measured values consistently increasing from 5.8 to 27.2 $g\ ha^{-1}\ min^{-1}$ as runoff rate increased from 2.3 to 22.9 $L\ min^{-1}$.

The contribution of PP to TP transport was substantially larger than that provided by DP. As runoff rate increased, the quantity of PP detached by overland flow can also be expected to increase. As a result, transport rates for TP increased significantly as runoff rate increased. Regression equations were derived relating rate of TP transport (y) in $g\ ha^{-1}\ min^{-1}$ to runoff rate (x) in $L\ min^{-1}$:

For the treatments containing a wheat strip:

$$y = 0.95x + 2.34 \quad (R^2 = 0.99)$$

For the treatments with no wheat strip:

$$y = 1.14x + 3.36 \quad (R^2 = 0.99)$$

The effects of runoff rate on runoff nutrient transport following the application of beef cattle manure to plots containing 0, 2, 4, or 8 $Mg\ ha^{-1}$ of corn residue were measured by Gilley et al. (2008b). Inflow was added to the top of each plot to produce runoff rates varying from 3.11 to 15.9 $kg\ min^{-1}$. The rate of transport of DP, PP, and TP were each significantly affected by runoff rate. In the present study, runoff rate was also significantly affected by the rate of transport of DP, PP, and TP.

Nitrogen Measurements

The presence of a wheat strip did not significantly affect runoff loads of NO_3-N, NH_4-N, or TN when inflow was added (table 3). Runoff loads of NO_3-N and NH_4-N varied from 3.6 to 8.4 $g\ ha^{-1}\ min^{-1}$ and from 0.9 to 8.8 $g\ ha^{-1}\ min^{-1}$, respectively. The relatively small concentrations of NO_3-N and NH_4-N in the applied manure of 0.01 and 0.15 $g\ kg^{-1}$, respectively (table 1), influenced the relatively small NO_3-N and NH_4-N loads measured in runoff.

Runoff loads of NO_3-N, NH_4-N, and TN were each significantly affected by runoff rate. As runoff rate increased from 2.3 to 22.9 $L\ min^{-1}$, NO_3-N and TN loads varied from 1.7 to 9.0 and from 26 to 127 $g\ ha^{-1}\ min^{-1}$, respectively. A regression equation was derived relating rate of TN transport (y) in $g\ ha^{-1}\ min^{-1}$ to runoff rate (x) in $L\ min^{-1}$:

$$y = 5.59x + 20.8 \quad (R^2 = 0.82)$$

Gilley et al. (2008b) also measured N transport from plots containing selected amounts of corn residue on which beef cattle manure was applied. The rates of transport of NO_3-N, NH_4-N, or TN were each found to be significantly affected by runoff rate. The results reported by Gilley et al. (2008b) are consistent with measurements obtained in the present study.

EC, pH, and Soil Loss Measurements

A mean EC value of 0.79 dS m^{-1} was measured when inflow was added (table 3). EC measurements increased from 0.78 to 0.80 dS m^{-1} as manure application rate varied from 0 to 36.6 Mg ha^{-1}. As runoff rate increased from 2.3 to 22.9 L min^{-1}, EC measurements decreased from 0.80 to 0.78 dS m^{-1}. The small variation in EC measurements among experimental treatments probably has little scientific significance.

Measurements of pH were not significantly affected by the presence of a wheat strip or manure application rate (table 3). However, runoff rate significantly influenced pH values, with measurements decreasing from 8.0 to 7.6 as runoff rate increased from 2.3 to 22.9 L min^{-1}. As runoff rate increased, the concentration of chemical constituents decreased due to dilution, causing pH to also decrease.

Soil loss rates were not significantly affected by the presence of a wheat strip or manure application rate (table 3). A mean soil loss rate of 19 kg ha^{-1} min^{-1} was measured at the experimental site. Soil loss measurements increased significantly with runoff rate, with values increasing from 5 to 40 kg ha^{-1} min^{-1} as runoff rate increased from 2.3 to 22.9 L min^{-1}.

Thayer et al. (2012) conducted a study to measure the effects of varying runoff rate on runoff nutrient loads following the application of beef cattle manure to plots on which manure was applied without incorporation at rates required to meet the 0-, 1-, 2-, 4-, or 8-year P-based requirements for corn. EC and pH measurements decreased significantly and soil loss rates increased significantly with runoff rates. The results reported by Thayer et al. (2012) are consistent with measurements obtained in the present investigation.

Water Quality of Runoff as Affected by Excessive Manure Application

Phosphorus Measurements

Runoff loads of DP and TP were not significantly affected by manure application rate when excessive amounts of manure were applied (table 4). As manure application rates increased from 73.2 to 183.0 Mg ha^{-1}, DP and TP loads increased from 0.29 to 0.64 kg ha^{-1} and from 0.70 to 1.59 kg ha^{-1}, respectively. No significant differences in PP loads were found among manure application rates varying from 73.2 to 146.4 Mg ha^{-1}. However, the PP load in runoff of 0.90 kg ha^{-1} measured for the manure application rate of 183.0 Mg ha^{-1} was significantly greater than that of the other application rates. Regression equations were derived relating P load (y) in kg ha^{-1} to manure application rate (x) in Mg ha^{-1}:

For DP: $y = 0.0035x + 0.069 \quad (R^2 = 0.86)$

For PP: $y = 0.0044x + 0.089 \quad (R^2 = 0.95)$

For TP: $y = 0.0079x + 0.16 \quad (R^2 = 0.92)$

It can be assumed that a substantial amount of P was available for transport at the higher manure application rates. The amount of DP and TP transported in runoff may have been influenced by the rate at which P was desorbed. The amount of P in runoff may have been limited by the rate of P desorption, not the quantity of manure on the soil surface.

Nitrogen Measurements

No significant differences in NH_4-N loads in runoff were found among manure application rates varying from 73.2 to 146.4 Mg ha^{-1} (table 4). However, the NH_4-N load in runoff of 1.17 kg ha^{-1} measured for the manure application rate of 183.0 Mg ha^{-1} was significantly greater than that of the other application rates. A regression equation was derived relating NH_4-N load in runoff (y) in kg ha^{-1} to manure application rate (x) in Mg ha^{-1}:

$$y = 0.0053x + 0.14 \quad (R^2 = 0.87)$$

Runoff loads of TN varied from 2.64 to 3.90 Mg ha^{-1} for the plots on which excessive amounts of manure were applied. Measured loads of NO_3-N were less than background levels of the simulated rainfall and therefore were not included in the analyses. The NO_3-N content of the applied manure was 0.01 g kg^{-1}, which influenced the small NO_3-N load measurements (table 1).

Relatively large amounts of NH_4-N and TN were present on the soil surface when excessive amounts of manure were applied. The rates at which NH_4-N and TN were desorbed, not the amount of manure contained on the soil surface, may have influenced the transport of NH_4-N and TN in runoff.

EC, PH, Runoff, and Erosion Measurements

EC varied from 1.16 to 1.90 dS m^{-1} as manure application rate increased from 73.2 to 183.0 Mg ha^{-1} (table 4). No significant differences in EC values were found among manure application rates varying from 73.2 to 146.4 Mg ha^{-1}. However, the EC value of 1.90 dS m^{-1} measured for the manure application rate of 183.0 Mg ha^{-1} was significantly greater than that of the other application rates. A greater number of chemical constituents was available for transport as the manure application rate increased. Therefore, EC values increased as manure application rate increased. A regression equation was derived relating EC (y) in dS m^{-1} to manure application rate (x) in Mg ha^{-1}:

$$y = 0.0066x + 0.78 \quad (R^2 = 0.98)$$

No significant differences in pH, runoff, or erosion were found among the plots where excessive amount of manure were applied. Measurements of pH decreased from 7.7 to 7.6 as the manure application rate increased from 73.2 to 183.0 Mg ha^{-1}. Mean runoff and erosion measurements

Table 4. Selected water quality parameters as affected by excessive manure application.[a]

Manure Rate (Mg ha^{-1})	DP (kg ha^{-1})	PP (kg ha^{-1})	TP (kg ha^{-1})	NH_4-N (kg ha^{-1})	TN (kg ha^{-1})	EC (dS m^{-1})	pH	Runoff (mm)	Erosion (Mg ha^{-1})
73.2	0.29 a	0.42 b	0.70 a	0.52 a	2.64 b	1.16 b	7.7 a	25 a	0.29 a
109.8	0.67 a	0.70 b	1.37 a	0.88 a	3.74 a	1.58 b	7.7 a	27 a	0.40 a
146.4	0.51 a	0.62 b	1.13 a	0.71 a	3.90 a	1.85 b	7.7 a	25 a	0.39 a
183.0	0.64 a	0.90 a	1.59 a	1.17 b	3.14 b	1.90 a	7.6 a	24 a	0.44 a

[a] Values followed by different letters are significantly different at the 0.05 probability level based on Student's t test.

were 25 mm and 0.38 Mg ha^{-1}, respectively.

Water Quality as Affected by Runoff Rate for Sites with Excessive Manure Application

Significant manure application rate by runoff rate interactions were found for PP, EC, and pH when inflow was added to the plots that received excessive amounts of manure (table 5). Manure application rate significantly influenced measurements of PP, TP, and EC. All of the measured water quality parameters were significantly affected by runoff rate.

Phosphorus Measurements

Runoff loads for DP were not significantly affected by manure application rate when inflow was added (table 5). However, the manure application rate significantly influenced loads of PP and TP in runoff. As the manure application rate increased from 73.2 to 183.0 Mg ha^{-1}, runoff loads of PP and TP increased from 12.0 to 55.4 g ha^{-1} min^{-1} and from 49.7 to 114 g ha^{-1} min^{-1}, respectively. Runoff loads of DP, PP, and TP were each significantly affected by runoff rate. As runoff rate increased from 2.5 to 22.0 L min^{-1}, DP, PP and TP loads in runoff increased from 17.6 to 59.7 g ha^{-1} min^{-1}, from 21.9 to 35.2 g ha^{-1} min^{-1}, and from 39.5 to 94.9 g ha^{-1} min^{-1}, respectively. Regression equations were derived relating rate of P transport (y) in g ha^{-1} min^{-1} to runoff rate (x) in L min^{-1}:

For DP: $y = 1.95x + 22.4 \quad (R^2 = 0.78)$

For PP: $y = 0.60x + 24.0 \quad (R^2 = 0.76)$

For TP: $y = 2.56x + 46.4 \quad (R^2 = 0.79)$

A relatively large amount of P was present on the experimental plots when excessive amounts of manure were applied. Two important variables influencing P transport are rate of P desorption and P transport capacity. The amount of P transported in runoff at the lower flow rates is influenced by P transport capacity. However, once P transport capacity exceeds the rate of P desorption, the rate of P desorption becomes the controlling variable and P losses become nearly constant.

Nitrogen Measurements

When inflow was added to the plots receiving excessive amounts of manure, runoff loads of NH_4-N and TN were not significantly affected by manure application rate (table 5). However, runoff rate significantly influenced runoff loads of NH_4-N and TN. As runoff rate increased from 2.5 to 22.0 L min^{-1}, the NH_4-N and TN loads in runoff increased from 27.4 to 45.5 g ha^{-1} min^{-1} and from 112 to 224 g ha^{-1} min^{-1}, respectively. A regression equation was derived relating rate of TN transport (y) in g ha^{-1} min^{-1} to runoff rate (x) in L min^{-1}:

$$y = 5.55x + 111 \quad (R^2 = 0.89)$$

A relatively large amount of N was present on the experimental plots when an excessive amount of manure was applied. The two important variables influencing N transport are rate of N desorption and N transport capacity. N transport capacity may be the principal variable influencing N transport at the lower flow rates. However, the rate of N desorption becomes the controlling variable once N transport capacity exceeds the rate of N desorption and N losses become nearly constant.

EC, PH, and Soil Loss Measurements

Manure application rate significantly affected EC measurements when inflow was added, with values increasing from 0.90 to 1.24 dS m^{-1} as manure application rate increased from 73.2 to 183.0 Mg ha^{-1} (table 5). The application of excessive amounts of manure provided additional chemical constituents available for transport by overland flow. Runoff rate also significantly influenced EC measurements, with values decreasing from 1.62 to 0.85 dS m^{-1} as the manure application rate increased from 2.5 to 22.0 L min^{-1} (table 5). As flow rates increased, the concentration of chemical constituents in solution was reduced, resulting in smaller EC measurements. A regression equation was derived relating EC (y) in dS m^{-1} to runoff rate (x) in L min^{-1}:

$$y = -0.033x + 1.50 \quad (R^2 = 0.75)$$

Values for pH were not significantly affected by manure application rate. However, runoff rate significantly influenced pH measurements, with values consistently decreasing from 7.7 to 7.5 as runoff rate increased from 2.5 to 22.0 L min^{-1}.

Soil loss rates were not significantly affected by manure application rate, and the mean soil loss value for the inflow tests was 26 kg ha^{-1} min^{-1} (table 5). Soil loss measurements consistently increased with runoff rate, with values varying

Table 5. Runoff water quality parameters as affected by excessive manure application rate and runoff rate.[a]

	DP (g ha^{-1} min^{-1})	PP (g ha^{-1} min^{-1})	TP (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})
Manure rate (Mg ha^{-1})								
73.2	37.7	12.0 b	49.7 b	18.0	91	0.90 b	7.6	24
109.8	38.4	26.3 b	64.7 b	34.6	129	1.15 ab	7.6	25
146.4	38.3	27.9 b	66.2 b	39.8	169	1.28 a	7.6	22
183.0	58.9	55.4 a	114 a	66.9	292	1.24 a	7.6	32
Runoff rate (L min^{-1})								
2.5	17.6 c	21.9 c	39.5 c	27.4 b	112 b	1.62 a	7.7 a	12 d
4.7	33.4 bc	29.0 bc	62.4 b	35.0 b	133 b	1.23 b	7.6 b	16 d
9.8	53.2 a	31.0 b	84.3 a	46.1 a	191 a	1.01 bc	7.6 b	25 c
14.4	52.5 a	34.9 b	87.4 a	45.0 a	191 a	0.99 cd	7.5 c	31 bc
22.0	59.7 a	35.2 a	94.9 a	45.5 a	224 a	0.85 d	7.5 c	44 a
ANOVA (Pr > F)								
Manure rate	0.44	0.01	0.02	0.09	0.09	0.01	0.06	0.58
Runoff rate	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Manure rate × runoff rate	0.88	0.03	0.37	0.37	0.09	0.01	0.04	0.75

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

from 12 to 44 kg ha^{-1} min^{-1} as runoff rate increased from 2.5 to 22.0 L min^{-1}.

Gilley and Eghball (1998) conducted a study that included a determination of the effects of a single application of manure on soil loss under no-till conditions. Soil loss was not affected by manure application. The results reported by Gilley and Eghball (1998) are consistent with the measurements obtained in the present study.

Comparison of Wheat Strips to Grass Hedges

Gilley et al. (2008a) conducted a field study to measure the effectiveness of a narrow grass hedge in reducing runoff nutrient transport from plots with a range of soil nutrient values. Composted beef cattle manure was applied at rates of 0, 68, 105, 142, and 178 Mg ha^{-1}, the amounts required to meet the 0-, 1-, 2-, 3-, or 4-year N requirements for corn. The manure was incorporated by disking following application to the 0.75 m wide × 4 m long plots located on an Aksarben soil with a 5% slope. Several months later, three 30 min simulated rainfall events, separated by 24 h intervals, were applied, and nutrient transport was measured.

Compost application rate was found to significantly affect the transport of DP, TP, and NO_3-N in runoff. The 1.4 m long grass hedge, which covered 35% of the plot area and contained both standing vegetation and residue materials, reduced runoff loads of DP, TP, NO_3-N, NH_4-N, and TN by 60%, 68%, 68%, 78%, and 48%, respectively. DP loads on the plots that did not contain a grass hedge increased significantly with each incremental increase of applied manure. In comparison, no significant increases in DP load were found among the plots containing a grass hedge when manure was applied at rates of 68, 105, and 178 Mg ha^{-1}.

The effectiveness of a 1.4 m wide grass hedge in reducing runoff nutrient loads following application of beef cattle manure was examined by Gilley et al. (2011). Manure was applied without incorporation to 0.75 m wide × 4 m long plots located on an Aksarben soil with a 3.8% slope. The manure was added at rates required to meet the 0-, 1-, 2-, or 4-year N requirements for corn. Three 30 min simulated rainfall tests, separated by 24 h intervals, were conducted soon after manure application.

Manure application rate significantly affected DP and TP loads in runoff on the plots without a grass hedge. The hedge reduced the mean load of DP in runoff from 0.69 to 0.08 kg ha^{-1} and the load of TP from 1.05 to 0.13 kg ha^{-1}. When averaged across manure application rates, 0.11 kg NO_3-N ha^{-1}, 0.02 kg NH_4-N ha^{-1}, and 0.49 kg TN ha^{-1} were measured from the plots with a hedge, compared to 0.39 kg NO_3-N ha^{-1}, 0.55 kg NH_4-N ha^{-1}, and 2.52 kg TN ha^{-1} from the plots without a hedge. For the plots with a grass hedge, runoff loads of DP and TP where manure was applied were similar to values obtained on the plots without manure.

In the present study, nutrient loads were measured from 0.75 m wide × 4 m long plots located on an Aksarben soil with a 4.8% slope. Beef cattle manure was applied without incorporation just before the rainfall simulation tests at rates required to meet the 0-, 1-, 2-, or 4-year P requirements for corn. The 4-year P application rate was slightly larger than the 1-year N requirement. The wheat strips, which were 1.4 m long, contained actively growing wheat plants and soybean residue and covered 35% of the plot area. Runoff loads of DP, PP, TP, NO_3-N, NH_4-N, and TN on the plots that contained wheat strips were reduced by 36%, 13%, 23%, 55%, 52%, and 51%, respectively.

The manure application rates selected in the studies by Gilley et al. (2008a, 2011) were substantially larger than those used in this investigation, and runoff loads of P and N were reduced significantly by the narrow grass hedges. In comparison, the reductions in P loads in runoff in the present study were not substantially larger than the 35% reduction in plot area provided by the wheat strip. The wheat strip used in the present study significantly reduced N loads in runoff, but the reductions in N loads were much less than those previously reported for narrow grass hedges (Gilley et al., 2008a, 2011). Therefore, the narrow wheat strips were much less effective than narrow grass hedges in reducing nutrient transport in runoff following application of beef cattle manure.

Effectiveness of Standing Wheat versus Wheat Residue

The winter wheat strips examined in this study were planted on September 30, 2009, and the rainfall simulation tests were performed from May 25 to June 17, 2010, while the wheat plants were actively growing. Thus, the crop residue on the soil surface during the tests consisted primarily of soybean residue remaining from the previous cropping season. Flow characteristics on upland areas can be described using the Darcy-Weisbach equation, and the Darcy-Weisbach roughness coefficient can be used to quantify hydraulic roughness (Chow, 1959).

For many cropland conditions, the contribution to total hydraulic roughness caused by standing crop materials is much smaller than that provided by crop residue. As an example, Darcy Weisbach roughness coefficients for wheat stalks located perpendicular to flow at a row spacing of 18 cm with a population of 93 stalks m^{-1} varied from 0.3 to 0.8 as Reynolds number ranged from 600 to 20,000 (Gilley and Kottwitz, 1994). In comparison, Darcy Weisbach roughness coefficients varied from 0.6 to 7 on a surface with a 70% wheat residue cover for Reynolds numbers ranging from 500 to 20,000 (Gilley et al, 1991). Thus, hydraulic roughness coefficients and associated resistance to overland flow will be much greater after the winter wheat is harvested and a substantial amount of wheat residue has accumulated on the soil surface. Small ponds formed upslope from a narrow strip containing substantial wheat residue may have been more effective in reducing nutrient loads in runoff than the standing wheat stalks examined in this investigation. Thus, narrow wheat strips may be more effective in reducing nutrient transport in runoff after harvest, when a much larger quantity of residue material is located on the soil surface.

Conclusions

The 1.4 m wide strips of actively growing wheat effectively reduced runoff loads of NO_3-N, NH_4-N, and TN. However, the wheat strips did not substantially reduce run-

off loads of DP, PP, and TP. Runoff loads of NH_4-N were found to increase in a linear fashion with manure application rate when excessive amounts of manure were applied.

Runoff loads of DP, PP, and TP were significantly affected by manure application rate. The application of manure to meet a 2-year rather than a 1-year P requirement for corn did not significantly increase DP, PP, or TP loads in runoff. However, runoff loads of DP, PP, and TP were significantly greater on the plots where manure was applied to meet a 4-year rather than a 2-year corn P requirement. Each of the measured water quality parameters were significantly influenced by runoff rate.

Our research indicates that narrow grass hedges are much more effective than actively growing wheat strips in reducing nutrient loads in runoff. Additional testing is needed to determine the effectiveness of narrow strips containing wheat residue in reducing runoff nutrient loads following wheat harvest.

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