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VEGETATED FILTER STRIP REMOVAL OF CATTLE MANURE CONSTITUENTS IN RUNOFF

T. T. Lim, D. R. Edwards, S. R. Workman, B. T. Larson, L. Dunn

ABSTRACT. *Pasture runoff can contribute to elevated concentrations of nutrients, solids, and bacteria in downstream waters. The objective of this study was to determine the effects of vegetative filter strip (VFS) length on concentrations and transport of nitrogen, phosphorus, solids and fecal coliform in runoff from plots treated with cattle manure. Three plots with dimensions of 2.4 × 30.5 m were used. The upper 12.2 m of each plot was treated with cattle manure, while the lower 18.3 m acted as a VFS. Runoff produced by rainfall simulators was sampled at VFS lengths of 0, 6.1, 12.2, and 18.3 m and analyzed for total Kjeldahl nitrogen (N), ammonia N, nitrate N, total phosphorus (P), ortho-P, fecal coliforms, total suspended solids and other parameters. The VFS significantly reduced concentrations and mass transport of incoming solids, fecal coliform, and most nutrient forms, particularly P. The relationships among VFS length, concentration and mass transport were well-represented by first-order exponential decay functions. Approximately 75% of incoming total Kjeldahl N, total P, ortho-P, and total suspended solids was removed within the first 6.1 m of the filter strips. Runoff concentrations of fecal coliform concentrations entering the filter strips were as high as* 2×10^7 *FC/100 mL; after a filter length of 6.1 m, however, the runoff exhibited no measurable concentration of fecal coliforms. This experiment suggests that even relatively short filter strips can markedly improve quality of runoff from grassed areas receiving cattle manure.*

Keywords. *Filter strips, Runoff, Water quality, Cattle manure, Fecal coliforms.*

Concern regarding the environmental impact of cattle grazing is common in areas having substantial animal production. The potential impacts of cattle manure entering streams, lakes and other waters are well established. For example, the decomposition of organic matter can cause dissolved oxygen concentrations to drop below respiration requirements of fish. Excessive inputs of nitrogen (N) and phosphorus (P) may accelerate eutrophication of water bodies and promote growth of aquatic weeds and algae. Waters that receive pasture runoff can also contain unacceptably high concentrations of indicator organisms such as fecal coliform (FC) that signal the possible presence of pathogenic microorganisms.

Even if the possible impacts of grazing on water quality are recognized, it is far from clear whether grazing at recommended stocking densities actually has any significant effect on downstream waters. The studies reported by Milne (1976), Doran and Linn (1979), Doran et al. (1981), and Gary et al. (1983), which collectively suggest mixed results regarding grazing impacts on surface water nutrient and bacteria concentrations, represent but a sampling of the associated work that has been undertaken in the last two decades. Despite the significant efforts involved in such studies, it is generally unclear whether there are consistently detectable water quality effects, especially with regard to nutrients, attributable to grazing at typical stocking densities. Whether there is even a grazing effect on runoff FC concentrations is apparently an open topic, since Edwards et al. (1997a) were unable to identify, based on runoff FC concentrations, periods during which cattle were present on pasture fields. The only proposal that seems to meet with near-universal acceptance is that it is better for manure to be deposited farther away from waters as opposed to nearer (or even directly in) (e.g., Larsen et al., 1994; Edwards et al., 1997). By direct implication, there is a water quality benefit associated with some intervening land area between manure and the water body of concern, i.e., a buffer zone.

Vegetated filter strips (VFS) are vegetated regions that receive and purify runoff from up-slope pollutant source areas, also known as buffer strips, buffer zones or filter strips (Chaubey et al., 1995). They are widely used and are increasingly viewed as a practical, low-cost management option for improving the quality of runoff from pollutant source areas. For the past few decades, researchers have demonstrated the effectiveness of VFS for sediment removal in runoff from strip mines, nutrients and solids removal from feedlot, pasture and cropland runoff, and treatment of municipal wastewater. Some studies showed that VFS can remove as much as 90% or more of incoming pollutants (e.g., Coyne et al., 1995). Gross et al. (1991) indicated that even low density turf stands greatly reduce sediment loss.

Despite their potential for markedly improving the quality of incoming runoff, VFS performance is not

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consistent across all topography and pollutants. Magette et al. (1989) pointed out that performance of VFS in reducing nutrients is highly variable. Some studies concluded that VFS were not sufficient for reducing runoff FC concentrations to primary contact standards (Walker et al., 1990; Coyne et al., 1995). Chaubey et al. (1994) pointed out that the VFS did not remove significant nitrate N (NO_3-N) or fecal coliform (FC) in a study involving swine manure. Dillaha et al. (1986) have vividly demonstrated that the flow regime within the VFS is critically important to good performance, with VFS removing far less pollutants for concentrated flow than for diffuse flow. Although it is apparent that VFS are generally capable of contributing to runoff quality improvements, the forms of the improvements and the design parameters for optimal performance are difficult to define.

Due in part to the uncertainty associated with predicting VFS performance, there are (and will undoubtedly continue to be) several different strategies available to select the best VFS length for a particular situation. Bingham et al. (1980) reported that a ratio of manure-treated area to VFS area of one was required to reduce runoff concentrations of various litter constituents to background levels. Edwards et al. (1996a) described a design procedure in which VFS length depends on soil, incoming pollutant concentrations, and goals with regard to pollutant reduction. Some service agencies recommend more-or-less standard VFS lengths with some flexibility depending on factors such as land slope. Since VFS typically replace land otherwise used for crop or forage production, there is a tendency to minimize filter areas. Appropriate procedures for determining optimal placement, dimensions and orientation of buffer area must be developed for VFS to be most effective and economical.

The objective of this study was to determine the effects of VFS length on concentrations and mass transport of N, P, solids, FC, and other parameters in runoff from cattle manure-treated plots. This study complements prior work in that most studies have addressed uses of VFS just beneath feed lots or row-cropped lands; this work addresses the effectiveness VFS installed down-slope of simulated grazed areas. The results can be useful in extending findings from prior VFS studies to pasture pollutant sources and can strengthen design procedures such as those suggested by Bingham et al. (1980) and Edwards et al. (1996a).

PROCEDURE

This experiment was conducted at the University of Kentucky Maine Chance Agriculture Experiment Station during the summer of 1996. The soil at the site is Maury silt loam (fine, mixed, mesic *Typic Paleudalf*). Earlier work at the site (Evans et al., 1998) indicated that the soil has a high water intake capacity; runoff as a proportion of applied rainfall ranged only from 1 to 21% for a 63 mm/h simulated rainfall event applied to grassed plots at the site. A good stand (100% cover with a mean height of approximately 10 cm) of Kentucky-31 “tall” fescue (*Festuca arundinacea* Schreb.) had been established on all experimental plots at the site. Irrigation was applied to the plots two to three times per week (if necessary) to promote vegetation growth and avoid summer dormancy. The vegetation height was maintained by using a commercial lawn mower and trimmer for weekly cutting and trimming.

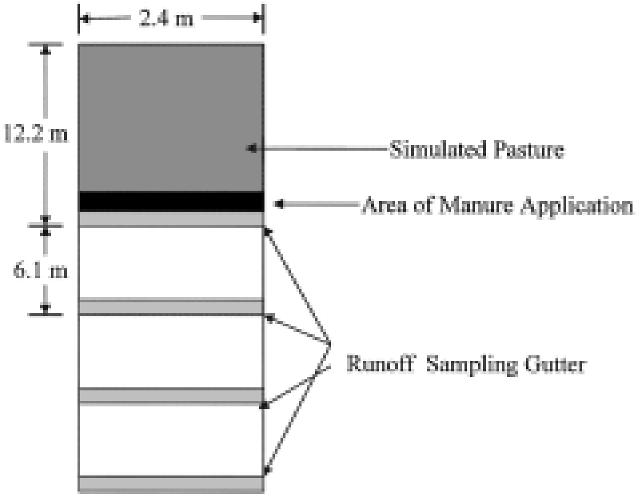

Figure 1–Schematic (not to scale) of experimental plot.

Three plots were used for the experiment. Each plot has dimensions of 30.5×2.4 m, oriented with major axes running up and down-slope (fig. 1). The plots are level across the minor axes and have a constant 3% slope along the major axes. Rustproof metal borders (4 cm exposed height) were installed around the plots to isolate runoff. Wooden gutters were installed along the length of each plot, distributed 6.1, 12.2, 18.3, 24.4, and 30.5 m from top, which separated the plots into five sections of equal areas. Removable watertight covers were installed on the gutters so that the runoff would simply cross the gutters and continue down slope when covered. These covers were designed to be easily removed to collect runoff samples when necessary. Each gutter was constructed to drain to one side of the plot, so that runoff samples could be collected by removing the cover when a sample was to be collected. The gutter slope is sufficient to minimize deposition of solid materials.

The upper 12.2 m of each plot was used to represent pasture and was treated with beef cattle manure, while the remainder of each plot acted as a VFS (fig. 1). The manure application rate was 60 kg N ha^{-1} (gross application of 7.8 kg manure). This rate of manure application is equivalent to the manure that would be produced from a stocking density of nine 450 kg animal units/ha for a seven-day grazing duration (ASAE, 1991), which would represent a heavily grazed condition. The manure was applied along the lower edge of the simulated pasture, so that high concentrations of manure constituents in runoff could be produced as input to the VFS. The rate of application and method of manure placement obviously were not selected to represent a typical stocking density or particular deposition pattern. The objective was to assess the effectiveness of VFS with regard to cattle manure constituents, so the manure application was structured to ensure sufficiently high incoming concentrations of manure constituents to evaluate VFS performance. Prior to manure application, approximately five soil samples (0-5 cm) were collected from each plot and analyzed (table 1). The soil samples were analyzed for parameters such as pH, organic matter (OM), total nitrogen (TN), calcium (Ca), zinc (Zn)

Table 1. Soil composition

Parameter	Plot 1 Mean*	Plot 2 Mean	Plot 3 Mean	Overall Mean	Overall CV†
pH	6.0	6.4	6.2	6.2	0.04
OM (%)	3.22	2.96	3.56	3.24	0.09
P (mg/kg)	86.70	99.70	93.00	93.13	0.07
K (mg/kg)	381.5	353.4	337.4	357.4	0.06
Ca (mg/kg)	1209	1560	1405	1391.6	0.13
Mg (mg/kg)	265.6	321.9	325.9	304.5	0.11
Zn (mg/kg)	2.10	1.53	2.11	1.91	0.17
TN (mg/kg)	1999	1830	1973	1933.7	0.05

* Mean of five samples, dry basis.

† Coefficient of variance.

Table 2. Cattle manure composition

Parameter	Mean* (mg/kg)	CV† (mg/kg)
H_20	814 800	0.03
Total N	22 500	0.16
P	5 840	0.03
K	3 400	0.48
Cu	36	0.58
Zn	114	0.36

* Mean of twelve samples, “as is” basis.

† Coefficient of variance.

Table 3. Municipal water composition

Parameter	Mean*	CV†
pH	8.08	0.00
NO_3-N (mg/L)	0.0003	0.57
NH_3-N (mg/L)	0.0004	0.75
TKN (mg/L)	0.56	0.26
PO_4-P (mg/L)	0.0001	1.00
TP (mg/L)	0.0093	1.08
TSS (mg/L)	1.10	0.27
TS (mg/L)	27.43	0.18

* Mean of three samples.

† Coefficient of variance.

and others. The cattle manure used originated from confined (indoor) beef cattle fed fescue hay as part of a separate experiment. The manure was collected by scooping it off a concrete floor and included no urine. The manure was collected one day before the experiment and refrigerated (1°C) until applied to the plots. The results of the manure analyses are given in table 2.

Five rainfall simulators (based on the design of Miller, 1987) per plot were used to generate runoff. The rainfall simulators were constructed by the Biosystems and Agricultural Engineering Department of the University of Kentucky. Each simulator was calibrated to ensure accurate rainfall intensities. The rainfall intensity used for this experiment was 100 mm h^{-1}, with municipal water as the source. This relatively high rainfall intensity (with a corresponding return period of > 100 years; Hershfield, 1961) was used to enhance runoff occurrence, since past work indicated high infiltration capacity at the site. The simulated rainfall was applied immediately after the application of cattle manure. The combination of intense simulated rainfall, its proximity to manure application, and the method of manure application can be considered as representing a “near-worst-case” scenario and constituted a rigorous test of the VFS.

Runoff samples were collected manually at specified intervals (2, 4, 8, 18, 30, 45, 60 min after the beginning of continuous runoff) at VFS lengths of 0, 6.1, 12.2, and 18.3 m during runoff. Since three plots were used in the study, this procedure resulted in three replications of each VFS length from 0 to 18.3 m. At a given sampling time, a runoff sample was collected first from the lower-most gutters and then the next gutter up the length of the experimental plots. A technician was stationed at each gutter and began collecting the sample from the particular gutter immediately following collection of the runoff sample from the next down-slope gutter. Sample volumes were in the range of 1.2 to 2 L. The time required to collect each sample was recorded, so that runoff rates could be computed. Three municipal water samples were also collected during the experiment and analyzed to determine background quality of the water source (table 3).

All runoff samples were weighed immediately after collection to determine sample masses and volumes. Measurements of pH were completed at the experiment site using a pH meter (Orion pH meter, model 290 A). All other laboratory analyses were performed prior to exceeding the holding times specified by Greenberg et al. (1992). Runoff samples were refrigerated at 1°C while awaiting analysis. Concentrations of total Kjeldahl N (TKN), ammonia N (NH_3-N), nitrate N (NO_3-N), ortho-P (PO_4-P), total P (TP), total suspended solids (TSS), total solids (TS), electrical conductivity (EC), and FC were analyzed in the Biosystems and Agricultural Engineering Department Chemistry Laboratory. Electrical conductivity was determined using an conductivity probe (ATI Orion waterproof conductivity meter, model 135). Standard methods (Greenberg at al., 1992) were used in the analyses of TKN (macro-Kjeldahl method), NH_3-N (phenate method), TSS (filtration and drying method), TS (drying method), TP (persulfate oxidation and ascorbic acid method), and FC (membrane filtration method). A method developed by van Veldhoven and Mannaerts (1987) was used to analyze concentrations of PO_4-P. Nitrate N concentrations were analyzed according to the method provided by Technicon (1978).

The concentration data and runoff data were jointly used to calculate flow-weighted mean runoff concentrations, mass transport, and mass removal effectiveness of analysis parameters. Mass removal effectiveness was calculated from:

$$E(x) = 100\left[\frac{M(0) - M(x)}{M(0)}\right] \quad (1)$$

where E is mass removal effectiveness (%), M is mass transport (g), and x is VFS length (m). The term M(0) is mass entering the VFS. The significance of VFS effects was assessed using analysis of variance (ANOVA). In cases where concentration or mass transport was significantly affected by VFS length, the data were fitted to the following first-order exponential decay models to calculate rate coefficients that can facilitate comparison to earlier studies:

$$C(x) = C_0e^{-kx} \quad (2)$$

$$M(x) = M_0 e^{-kx} \tag{3}$$

In the above two equations, C is concentration (mg/L), M is mass transport (mg), x is VFS length, and C_O, M_o, and k are coefficients (k is the rate coefficient). For data that are described perfectly by equations 2 and 3, the coefficients C_0 and M_0 will be equal to the initial concentration and mass transport, respectively. The coefficients C_O, M_o and k were determined through linear regression using the natural logarithms of both sides of equation 2 and 3 (i.e., C_0 and M_0 were not constrained to be equal to the initial concentration and mass transport, respectively).

RESULTS

CONCENTRATIONS

Analysis of variance indicated that concentrations of all parameters except pH, NO_3-N, and NH_3-N were significantly ($p < 0.05$) affected by VFS length. Mean runoff pH was 7.89, which is similar to that of the water used to simulate rainfall (table 3). Mean NO_3-N and NH_3-N concentrations in runoff were 0.20 and 0.65 mg/L, respectively, averaged over all treatments and replications. Both are substantially greater than corresponding concentrations in the simulated rainfall (table 3), but comparable to "background" concentrations measured in runoff from plots having no manure applied (Edwards et al., 1998b). This information indicates that the NO_3-N and NH_3-N concentrations measured in this study basically represent "background" concentrations, and that the manure added no significant NO_3-N or NH_3-N to the soil (particularly since no urine was included). This finding was expected, since the manure was fresh (< 24 h old) and had been refrigerated since deposition, allowing little opportunity for mineralization to occur.

Statistics of parameters that were affected by the VFS are given in table 4. Each parameter listed in table 4 exhibited significant decreases in response to increasing VFS length. As indicated by results of the mean separations, however, no significant reductions in concentrations occurred beyond a VFS length of 6.1 m. The first order model of equation 2 generally explained a significant proportion of variation in the concentration data, particularly for TSS and TKN, with coefficients of determination ranging from 0.37 (TSS) to 0.96 (TKN). Fitted first-order models are demonstrated in figure 2 for TKN and PO_4-P.

Table 4. Mean* runoff concentrations of cattle manure constituents

	VFS Length (m)				
Parameter	0	6.1	12.2	18.3	k† (m^{-1})
TKN (mg/L)	10.12a‡	2.04b	1.22b	1.00b	0.12 ($r^2 = 0.84$)
PO_4-P (mg/L)	1.28a	0.31b	0.17b	0.23b	0.09 ($r^2 = 0.69$)
TP (mg/L)	1.42a	0.32b	0.15b	0.23b	0.10 ($r^2 = 0.68$)
FC (FC/100mL)	1.8×10^6a	0.00b	0.00b	0.00b	0.70 ($r^2 = 0.60$)
TSS (mg/L)	133.74a	37.54b	22.44b	10.85b	0.13 ($r^2 = 0.96$)
TS (mg/L)	525.83a	367.19b	409.86b	396.72b	NS§
EC (µs/cm)	611.91a	558.10b	556.12b	547.13b	NS

* Mean of three replications.
† First-order rate coefficient for equation 2; r^2 is coefficient of determination.
‡ Within-row means followed by the same letter are not significantly different different by LSD test.
§ Not significant ($p > 0.05$).

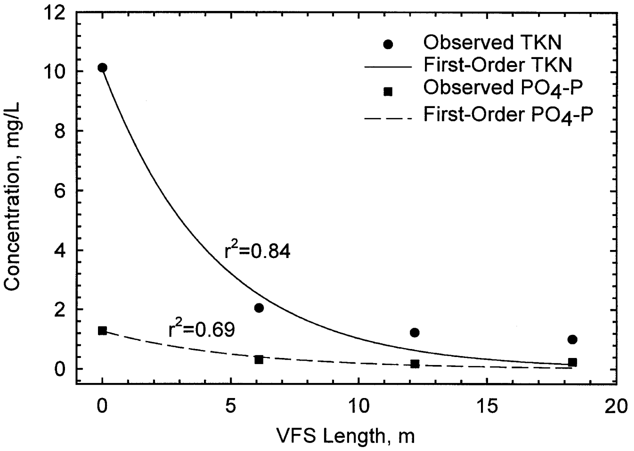

Figure 2–Observed and first-order predictions of TKN and PO_4-P concentrations as functions of VFS length.

Virtually all the P in the runoff was in the soluble PO_4-P form rather than associated with sediment (table 4); therefore, it is likely that infiltration was the primary removal mechanism for P. The VFS was effective in removing both suspended and total solids from runoff (table 4), but it appears that little dissolved solids were removed by the VFS, a view that is supported by the similar EC values. Instead, nearly all the reduction in TS can be attributed to TSS reduction by the VFS. It is possible that the manure itself contributed little to runoff dissolved solids, and that the dissolved solids in the runoff reflect background contributions from the soil rather than from the manure, similar to the NO_3-N and NH_3-N. The performance of the VFS with regard to FC concentrations was particularly encouraging, given the mixed history of VFS in restoring runoff to primary or even secondary contact standards. Incoming FC concentrations in runoff were as high as 2×10^7/100 mL; as shown in table 4, though, none were detected after the runoff had traversed a VFS length of 6.1 m, which was likely due to high infiltration within the plots. An average of 74 mm simulated rainfall was required to produce runoff from the plots, and runoff as a proportion of total simulated rainfall averaged only 1.8%. Therefore, significant transport of FC through the soil surface with the infiltrating water was likely. The FC reduction is not attributed to the presence of residual chlorine (Cl) in the simulated rainfall water. Total Cl in the water source used for simulated rainfall typically ranges from 1.5 to 2.5 mg/L (White, 1998, personal communication), which is considerably less than the range of 6-12 mg/L recommended for disinfection of raw sewage (Corbitt, 1990). In addition, the time required for runoff to travel from the 0 VFS length to the 6.1 m length can be computed Haan et al. (1994) as approximately 20 s, which is much less than the contact time of 900 to 1800 s recommended by Corbitt (1990).

MASS TRANSPORT

It has been noted in other studies (e.g., Chaubey et al., 1995) that VFS can lead to decreased runoff concentrations of various pollutants without actually removing any of these pollutants due simply to dilution. Calculations of

Table 5. Mean* runoff mass of cattle manure constituents

	VFS Length (m)				
Parameter	0	6.1	12.2	18.3	k† (m^{-1})
TKN (mg)	11,135a†	2,443b	1,039bc	452.1c	0.17 (r^2=0.98)
PO_4-P (mg)	1,408a	362.7b	161.5b	90.6b	0.15 (r^2=0.96)
TP (mg)	1,563a	382.3b	143.5b	92.0b	0.16 (r^2=0.95)
TSS (mg)	147,945a	44,273b	15,074b	3,798b	0.20 (r^2=0.99)
TS (mg)	587,986a	438,164ab	347,445ab	183,969b	0.07 (r^2=0.94)

* Mean of three replications.

† Within-row means followed by the same letter are not significantly different different by LSD test.

‡ First-order rate-coefficient for equation 3; r^2 is coefficient of determination.

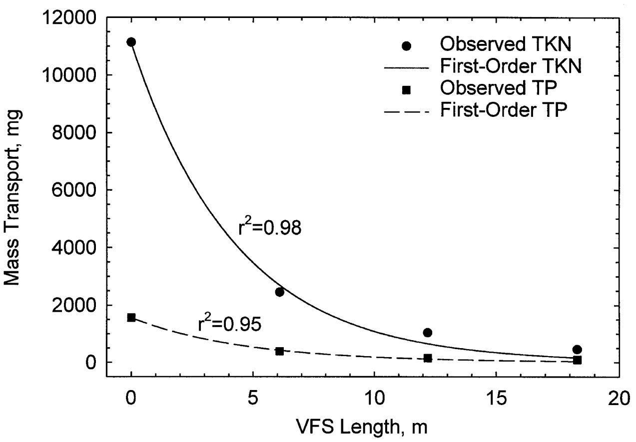

Figure 3–Observed and first-order predictions of TKN and TP mass transport as functions of VFS length.

mass transport for the pollutants of table 4 (table 5), however, indicated that the VFS removed significant proportions of incoming pollutants. The first-order model of equation 3 explained even more variation in the mass transport data than in the concentration, with coefficients of determination ranging from 0.94 to 0.99, as demonstrated in figure 3 for TKN and TP. The rate constants reported in table 5 are similar to those reported for VFS used to treat runoff from areas treated with swine manure (Chaubey et al., 1994) and poultry litter (Chaubey et al., 1995). These findings reinforce recommendations from Overcash et al. (1981) and Edwards et al. (1996a) regarding use of first-order models for designing VFS to remove soluble pollutants in incoming runoff.

Except for the case of TKN, VFS lengths greater than 6.1 m had no significant effect on mass transport. In terms of mass transport, then, there was no benefit associated with VFS lengths greater than 6.1 m. Another noteworthy characteristic of table 5 is that mass transport of nutrients was quite low (usually less than 2 g), even for this relatively severe scenario. This strongly suggests that nutrient losses from grazed pasture can be insignificant from an agronomic standpoint, and that the VFS will yield negligible return on the investment in terms of retaining beneficial nutrients. The impetus for installing them might be more properly related to environmental quality rather than production considerations. Calculated values of mass removal effectiveness are given in table 6. Except for the case of TSS, there were no improvements in overall effectiveness for VFS lengths greater than 6.1 m.

Table 6. Vegetative filter strip mass removal effectiveness*

	Mass Removal Effectiveness (%)		
Parameter	6.1 m	12.2 m	18.3 m
TKN	78.0a†	89.5a	95.3a
PO_4-P	74.5a	87.8a	93.0a
TP	76.1a	90.1a	93.6a
TSS	70.0a	89.5b	97.6b
TS	23.6a	40.8a	69.8a

* Mean of three replications.

† Within-row means followed by the same letter are not significantly different different by LSD test.

IMPLICATIONS OF LONGER POLLUTANT SOURCES

In practical application, it is likely that the areas that contribute runoff and pollutants to the VFS will have lengths of greater than 12.2 m, as used in this study. In the case of longer pollutant sources, incoming runoff can be expected to increase generally linearly with length. Even though results described by Edwards et al. (1996) suggest that concentrations might be unaffected by increasing source length, the increased runoff would lead to accompanying increases in pollutant masses entering the VFS. The results of this study can not be used directly to assess the effects of longer source lengths buffer strip performance, but previous reports are helpful in predicting the degradation of performance as related to increasing source length.

Overcash et al. (1981) modeled steady-state VFS performance in terms of reducing incoming concentrations of soluble pollutants as:

$$p_C = \left[1 - e^{\left(\frac{1}{1-D}\right)\ln\left(\frac{1}{1+K}\right)}\right] \qquad (4)$$

$$p_M = \left[1 - \left(1 + K\right) e^{\left(\frac{1}{1-D}\right)\ln\left(\frac{1}{1+K}\right)}\right] \qquad (5)$$

where

p_C = reduction (as proportion of incoming value) in concentration of pollutant entering the VFS
p_M = reduction (as proportion of incoming value) in mass transport of pollutant entering the VFS
D = ratio of infiltration to total rainfall
K = ratio of VFS to pollutant source length

Using an example value of 0.75 for D and letting the source and VFS be 12.2 and 6.1 m, respectively (resulting in K = 0.5), then equations 4 and 5 predict concentration and mass transport reductions of 0.80 and 0.70, respectively. If the source length were increased to, for example, 61 m, then K would be 0.1, and the concentration and mass transport reductions are calculated as 0.32 and 0.25, respectively. Hence, in this example, a five-fold increase in source length would lead to a 60% and 64% degradation of VFS performance in terms of concentration and mass transport, respectively. Equations 4 and 5 as well as procedures described by Edwards et al. (1996) can be used to predict VFS performance for a wider range of source lengths, VFS lengths, and infiltration-to-rainfall ratios.

SUMMARY AND CONCLUSIONS

This study assessed VFS length effects on quality of runoff from cattle manure-treated plots. Cattle manure was applied (60 kg N ha^{-1}) to the upper 12.2 m of grassed plots, while the lower 18.3 m functioned as VFS for runoff produced by simulated rainfall (100 mm h^{-1}). Runoff samples were collected at VFS lengths at 0, 6.1, 12.2, and 18.3 m and analyzed for various manure constituents. Analyses of variance were performed to determine the effects of VFS length on flow-weighted mean constituent concentrations.

Results showed that the VFS removed significant FC, PO_4-P, TSS, TS, EC, TKN, and TP from incoming runoff. No concentration reductions were observed for VFS length of greater than 6.1 m, similar to results reported by Edwards et al. (1996b) for VFS lengths of greater than 3 m. The removal of FC was found to be 100% after a VFS length of 6.1 m, likely due to high plot infiltration. This is an encouraging finding, because similar studies (Chaubey et al., 1995; Coyne at al., 1995; Walker et al., 1990) found VFS to be ineffective in removing FC. However, the VFS in this study did not remove significant incoming NO_3-N and NH_3-N (similar to other studies), likely due to small amounts of mineral N in the applied cattle manure. Although runoff NH_3-N concentration was not significantly affected by VFS length, the data suggested a decreasing trend with increasing VFS length. Had more NH_3-N been present in the manure (and thus the runoff), a significant VFS effect on runoff concentrations might have been noted.

Concentrations and mass transport of the analysis parameters were generally well-described by a first-order exponential relationship between concentration/transport and VFS length. This finding lends further support to the validity of using first-order relationships such as that developed by Overcash et al. (1981) to assist in designing VFS for removal of soluble pollutants. While the empirical findings of this study are necessarily specific to the experimental conditions, methods referenced and demonstrated in this article can be used to predict VFS performance under conditions of different VFS lengths and infiltration.

Even though they are a necessary first step, the findings of this study can not be directly translated to potential ecological benefits of VFS implementation. Relating VFS performance to ecological impacts would require detailed information on such factors as the stream, river or lake of interest; the chemical composition of the water and sediments; quantity and quality of runoff from all sources; and response dynamics of the plants/animals of interest. An analysis of ecological impacts would also probably be more site-specific than an analysis of VFS performance alone. Despite the challenges, such investigations should be undertaken since the true focus of agricultural water quality research is ultimately environmental (human, animal and plant) impacts rather than only edge-of-field reductions in concentrations or transport.

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