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PERFORMANCE OF VEGETATIVE FILTER STRIPS WITH VARYING POLLUTANT SOURCE AND FILTER STRIP LENGTHS

P. Srivastava, D. R. Edwards, T. C. Daniel, P. A. Moore Jr., T. A. Costello

ABSTRACT. *Vegetative filter strips (VFS) can reduce runoff losses of pollutants such as nitrogen (N) and phosphorus (P) from land areas treated with fertilizers. While VFS effectiveness is considered to depend on lengths of pollutant source and VFS areas, there is little experimental evidence of this dependence, particularly when the pollutant source is manure-treated pasture. This study assessed the effects of pollutant source area (fescue pasture treated with poultry litter) length and VFS (fescue pasture) length on VFS removal of nitrate N (NO_3-N), ammonia N (NH_3-N), total Kjeldahl N (TKN), ortho-P (PO_4-P), total P (TP), total organic carbon (TOC), total suspended solids (TSS), and fecal coliform (FC) from incoming runoff. This research examined poultry litter-treated lengths of 6.1, 12.2, and 18.3 m, with corresponding VFS lengths of up to 18.3 m, 12.2 m, and 6.1 m, respectively. Runoff was produced from simulated rainfall applied to both the litter-treated and VFS areas at 50 mm/h for 1 h of runoff. Pollutant concentrations in runoff were unaffected by litter-treated length but demonstrated a first-order exponential decline with increasing VFS length except for TSS and FC. Runoff mass transport of NH_3-N,TKN, PO_4-P, TP and TOC increased with increasing litter-treated length (due to increased runoff) and decreased (approximately first-order exponential decline) with increasing VFS length when affected by VFS length. Effectiveness of the VFS in terms of NH_3-N, TKN, PO_4-P, TP and TOC removal from runoff ranged from 12-75, 22-67, 22-82, 21-66, and 8-30% respectively. The data from this study can help in developing and testing models that simulate VFS performance and thus aid in the design of VFS installed downslope of pasture areas treated with animal manure.*

Keywords. *Non-point source pollution, Vegetative filter strips, Poultry litter.*

Land application of manure associated with concentrated animal production is a beneficial practice in terms of increasing soil fertility and improving soil physical characteristics. Studies such as reported by Westerman et al. (1983, 1985, 1987) and Edwards and Daniel (1993), however, demonstrate that manure application can elevate runoff concentrations of manure constituents such as carbon (C), nitrogen (N), and phosphorus (P). Excessive losses of manure constituents can, in turn, ultimately lead to undesirable downstream water quality impacts such as accelerated eutrophication and diminished suitability for aquatic wildlife. Studies and programs devoted to controlling runoff losses of nonpoint source pollutants are in general agreement that these losses are best controlled at their respective sources, rather than after entering streams and lakes.

Vegetative filter strips (VFS) have been widely investigated as a management option for retaining potential pollutants at or near their origin and thus minimizing their entry into downstream waters. Vegetative filter strips consist of areas of grass (or other vegetation) installed downslope of pollutant source areas. Considerable work has been conducted to determine how to best design VFS and to assess their effectiveness. The majority of these studies have focused on using VFS to improve the quality of runoff originating from feedlots and row-cropped pollutant source areas. Reported studies of VFS applied downslope of pollutant sources other than feedlots or row cropped land are relatively limited.

Young et al. (1980) used VFS plots with a slope of 4% to purify runoff originating from a feedlot. These plots were planted in either corn (*Zea mays* L.), orchard grass (*Dactylis glomerata* L.), oats (*Avena sativa* L., 'Froker'), or a mixture of sorghum (*Sorghum vulgare* L.) and sudangrass (*Sorghum sudanense* L.). Total runoff, sediment, total P (TP), total N (TN), total coliform, fecal coliform (FC), and fecal streptococci (FS) were reduced by 61 to 87% from the incoming amounts. Dickey and Vanderholm (1981) studied feedlot runoff and found that VFS removed as much as 95% (on mass basis) of nutrients and oxygen-demanding materials from the incoming runoff with concentration reductions of up to 80%. Edwards et al. (1983) and Dillaha et al. (1986b, 1988) also studied the effectiveness of VFS with regard to feedlot runoff and obtained similar results on the removal of solids, TP, and TN.

Dillaha et al. (1985, 1986a, 1987, 1989), Hayes and Hairston (1983), and Mickelson and Baker (1993) assessed the effectiveness of VFS in controlling pollutants from cropland runoff. These researchers found that VFS were up to 84%, 79%, 73%, and 56% effective in removing incoming masses of suspended solids, P, N, and atrazine, respectively.

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Doyle et al. (1975) applied dairy manure to plots having a slope of 4% and planted in alfalfa (*Medicago sativa*). Losses of FC, FS, TN, and soluble P were reduced, on an average, by more than 90% by a 30.5 m, forest filter strip. Bingham et al. (1980) applied caged-layer poultry manure to fescue (*Festuca arundinacea* Schreb) plots 13 m long, and reported that a VFS length to manure-treated length ratio of about 1.0 reduced pollutant loads to near background concentrations.

The objective of this study was to determine the effects of VFS length and pollutant source area length on the effectiveness of VFS installed downslope of grassed areas treated with poultry litter. The specific null hypotheses to be tested were that: (1) length of pollutant source area has no effect on VFS performance (assessed in terms of pollutant concentrations, mass transport and mass removal effectiveness); and (2) VFS length has no affect on VFS performance. This study contributes to information on VFS performance by examining manure-treated grassed areas as a pollutant source and by using poultry litter (a combination of manure and bedding material) as the manure treatment.

As pointed out earlier, there are few published accounts (e.g., Chaubey et al., 1993) of using grassed pollutant source areas and poultry litter in comparison to reports involving feedlot and crop land source areas and cattle manure and/or other materials. This study thus strengthens the body of information on VFS performance for applications in which manure from confined poultry production are land-applied to grassed areas. More importantly, however, this study contributes information on the effects of varying pollutant source area lengths on the performance of the downslope VFS. It is widely recognized that the performance of a fixed VFS length with respect to a particular pollutant depends on, among other things, the mass rate of entry of that pollutant into the VFS. The proportion of incoming pollutant mass that is removed by a VFS of given length generally decreases with increasing mass loading rate and, therefore, with increasing length of pollutant source area. Overcash et al. (1981) accounted for this process in their model of VFS performance for soluble pollutant filtration. Experimental investigations of VFS performance, however, have generally not examined the impact of pollutant source area length, *per se*. Rather, almost all VFS field experiments have used constant pollutant source area lengths and variable VFS lengths. This study involved assessing not only the performance of various VFS lengths, but also explicitly investigated the effects of pollutant source area length on VFS performance.

MATERIALS AND METHODS

The nine, 1.5 m × 24.4 m plots used for the experiment were constructed on a Captina silt loam soil (fine-silty, mixed, mesic, Typic Fragiudult) at the Main Agricultural Experiment Station of the University of Arkansas, Fayetteville. Each plot was cross-leveled and had a uniform slope of 3% along the long axis. Fescue (*Festuca arundinacea* Schreb.) was the dominant grass cover. All plots had wooden borders (10 cm belowground and 10 cm aboveground) to isolate runoff. Wooden gutters were installed across each plot at every 3 m downslope to collect runoff samples at those locations (fig. 1). The gutters were fitted with removable, water-tight sheet metal covers to prevent the entry of water when a runoff sample was not being collected.

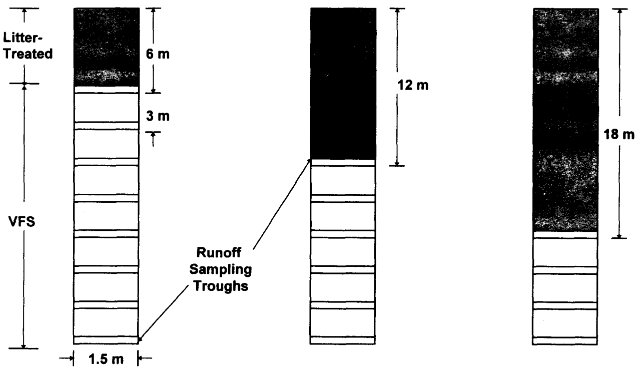

Figure 1–Schematic of plots (not to scale).

Soil samples (0-2.5 cm) were collected from each plot prior to poultry litter application. The soil samples were analyzed for pH, moisture content, electrical conductivity (EC), organic matter content, phosphorus (P), potassium (K), iron (Fe), copper (Cu), ammonium N (NH_4-N), nitrate N (NO_3-N), and total Kjeldahl N (TKN) using standard methods of analysis (Page et al., 1982) by the Agricultural Diagnostic Services Laboratory of the University of Arkansas. The results of the soil analyses are given in table 1.

The poultry litter applied to the plots was also sampled and analyzed prior to application for pH, EC, moisture content, TN, P, K, Fe, Cu, NH_4-N, and NO_3-N by the Agricultural Diagnostic Services Laboratory of University of Arkansas (table 2). The combustion method (Campbell, 1991) was used to determine total N. Inorganic N species

Table 1. Soil analysis results

Parameter	Value*
H_2O (%)	20.37 (0.16)†
Organic matter (%)	1.39 (0.26)
pH	5.5 (0.03)
EC (mmhos/cm)	20 (0.08)
NH_4-N (mg/kg)	1.7 (0.36)
NO_3-N (mg/kg)	2.1 (0.70)
TKN (mg/kg)	713.1 (0.28)
P (mg/kg)	59.7 (0.61)
K (mg/kg)	69.7 (0.13)
Fe (mg/kg)	113.9 (0.33)
Cu (mg/kg)	19.1 (0.86)

* Mean of 9 samples, "as is" basis.

† Coefficient of variation.

Table 2. Poultry litter analysis results

Parameter	Value*
H_2O (%)	24.85 (0.04)†
pH	7.16 (0.01)
EC (mmhos/cm)	7284 (0.09)
Total N (mg/kg)	26 105 (0.08)
NH_4-N (mg/kg)	1 088 (0.16)
NO_3-N (mg/kg)	78 (0.25)
P (mg/kg)	10 795 (0.07)
K (mg/kg)	19 315 (0.05)
Fe (mg/kg)	116 (0.64)
Cu (mg/kg)	417 (0.12)

* Mean of 20 samples, "as is" basis.

† Coefficient of variation.

were determined by extraction with 2 M potassium chloride followed by distillation. Amounts of P, K, Fe, and Cu in the litter were determined by preparing the samples according to Campbell and Plank (1991) followed by digestion with nitric acid and analysis by the inductively coupled plasma method (Donohue and Aho, 1991). Moisture content was determined using the gravimetric method. Electrical conductivity and pH analyses were performed on water:litter mixtures of 1:1 and 1:2, respectively.

The experimental design was an unbalanced factorial with three pollutant source area lengths (6.1, 12.2, and 18.3 m) and six VFS lengths (0, 3.1, 6.1, 9.2, 12.2, 15.3, and 18.3 m) as shown in figure 1. The configuration of the plots resulted in three replications of each pollutant source area length. The maximum VFS length investigated varied with pollutant source area length. As shown in figure 1, maximum VFS lengths of 18.3, 12.2, and 6.1 m were examined downslope of pollutant source area lengths of 6.1, 12.2, and 18.3 m, respectively.

Portions of the plots that were designated as pollutant source areas were treated with poultry litter applied manually as uniformly as possible. The litter application rate was 146.4 kg N/ha, a rate chosen to be compatible with the recommendation for fescue in Arkansas (Chapman et al., 1992). Application rates of selected poultry litter constituents are given in table 3.

Rainfall simulators were used to apply rainfall on the plots immediately following litter application. The simulated rainfall was applied to both the litter-treated (pollutant source) and untreated (VFS) portions of each plot. The municipal water used as simulated rainfall was sampled and analyzed (as described later) for various constituents as shown in table 4. A simulated rainfall intensity of 50 mm/h was used to facilitate comparison of results with similar studies (Chaubey et al., 1993). The simulated rainfall continued until 1 h after the start of runoff occurred at the downslope ends of the plots. Runoff was sampled manually (approximately 1 L sample size) at 0.04 h after runoff began and at 0.16 h intervals thereafter at each sampling location. Runoff samples corresponding to a particular sampling time were collected by first collecting a sample from the downslope end of the plot and then successively sampling each collection point up the length of the plot. Runoff rates and volumes at the downslope ends of the plots were determined by measuring both runoff sample volume and the time required to collect the sample. Runoff rates and volumes at the other sampling points were considered to be directly proportional to those measured at the corresponding end-of-plot sampling points (i.e., the proportionality constant was the area ratio). The assumption of linearly-increasing runoff rates and volumes would not affect any of the following concentration data; the effect on mass transport computations, if any, should be minimal due to relatively short travel times involved. The runoff data were used to form a single flow-weighted composite sample for each sampling point from the corresponding seven samples collected over the 1 h of runoff.

Table 3. Application rates of poultry litter constituents

Constituent	Application Rate (kg/ha)
Total N	146.4
NH_3-N	6.1
NO_3-N	0.5
Total P	60.3
K	108.3
Fe	0.7
Zn	2.7
Cu	2.3

Table 4. Simulated rainfall composition

Constituent	Concentration* (mg/L)
TKN	0.320
NH_3-N	0.020
NO_3-N	0.026
Total P	0.036
PO_4-P	0.021

* Mean of three samples.

Immediately following formation of composite samples, the samples were split into two portions. One portion was filtered through 0.45 μm pore diameter filter paper for NO_3-N and PO_4-P analysis. The runoff samples were then refrigerated (4°C) until analyzed. Standard methods (Greenberg et al., 1992) were used by the Arkansas Water Resources Center (AWRC) Water Quality Laboratory to analyze the unfiltered runoff samples for TKN, NH_3-N, TP, TOC, TSS, and FC. The AWRC Water Quality Laboratory routinely follows approved lab practices with regard to quality control (use of blank and spiked samples, etc.). The ammonia-selective electrode method was used for NH_3-N analysis. An ion chromatograph (Dionex DX-300 Gradient Chromatography System) was used to analyze NO_3-N and PO_4-P. The micro-Kjeldahl method was used for TKN analysis. Total P was analyzed using ascorbic acid colorimetric method following digestion in sulfuric acid-nitric acid. Total organic C was determined by the combustion-infrared method. Fecal coliform concentrations were measured using the membrane filtration technique.

The runoff volumes and litter constituent concentration data were used to compute mass transport of constituents past each sampling location. Analysis of variance (ANOVA) was performed to assess the influences of litter-treated length and VFS length on concentrations and mass transport of poultry litter constituents as well as on VFS effectiveness.

RESULTS AND DISCUSSION

POLLUTANT CONCENTRATIONS

Results from the ANOVA indicated that concentrations of the investigated pollutants (TKN, NH_3-N, NO_3-N, TP, PO_4-P, TOC, TSS, and FC) were not significantly influenced ($p > 0.10$) by litter-treated length. In other words, the concentrations of pollutants upon entering the VFS did not depend on the length of litter-treated distance over which the runoff had flowed prior to reaching the VFS. The insignificant effect of litter-treated length on pollutant concentrations could help simplify VFS design considerably from the standpoint of estimating incoming pollutant concentrations. This finding has been investigated in greater detail and corroborated by Edwards et al. (1996).

Concentrations of all pollutants except TSS and FC were significantly ($p < 0.003$) affected by VFS length. The pollutants that were influenced by VFS length (NO_3-N, NH_3-N, TKN, PO_4-P, TP, TOC) exhibited an approximately first-order exponential declining response to increasing VFS length (figs. 2-7). Means testing indicated

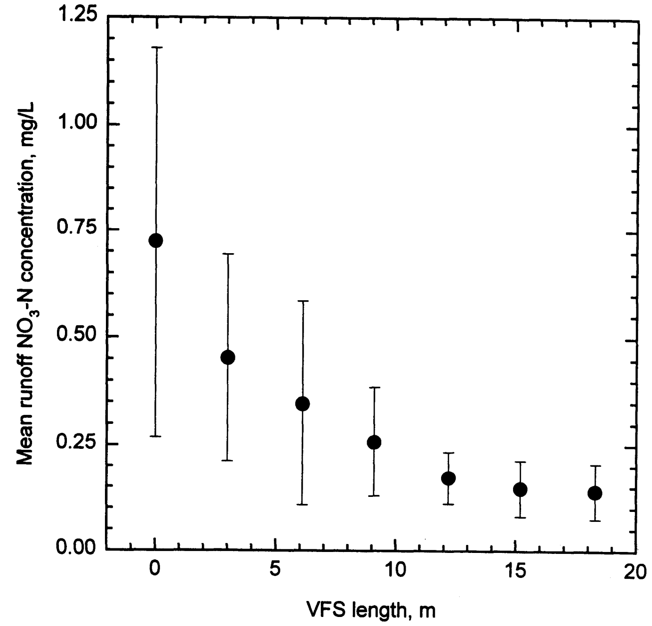

Figure 2–Effect of vegetative filter strip (VFS) length on runoff nitrate nitrogen (NO_3-N) concentration. Filled circles indicate means, and total bar length is two standard deviations.

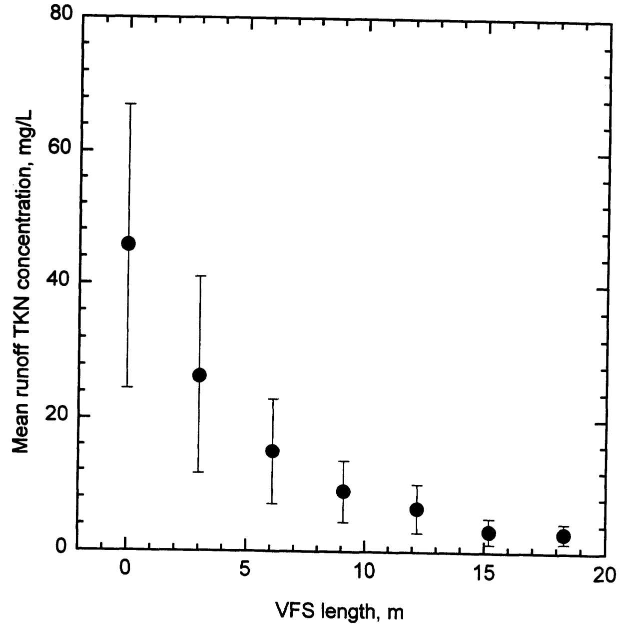

Figure 4–Effect of vegetative filter strip (VFS) length on runoff total Kjeldahl nitrogen (TKN) concentration. Filled circles indicate means, and total bar length is two standard deviations.

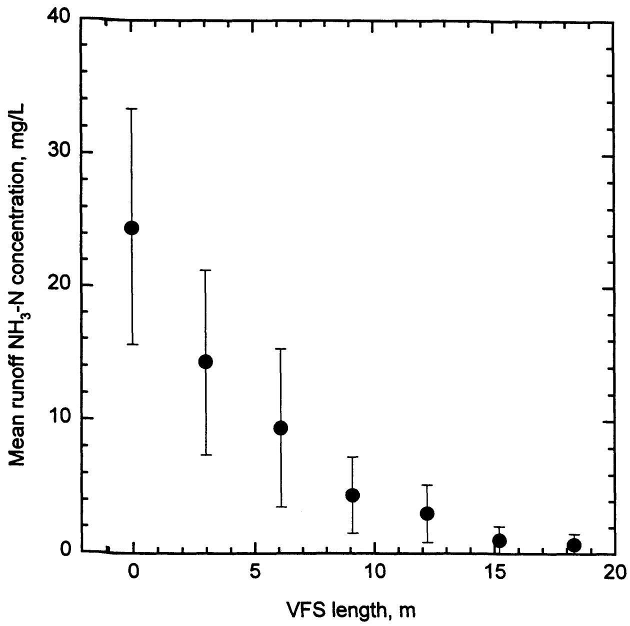

Figure 3–Effect of vegetative filter strip (VFS) length on runoff ammonia nitrogen (NH_3-N) concentration. Filled circles indicate means, and total bar length is two standard deviations.

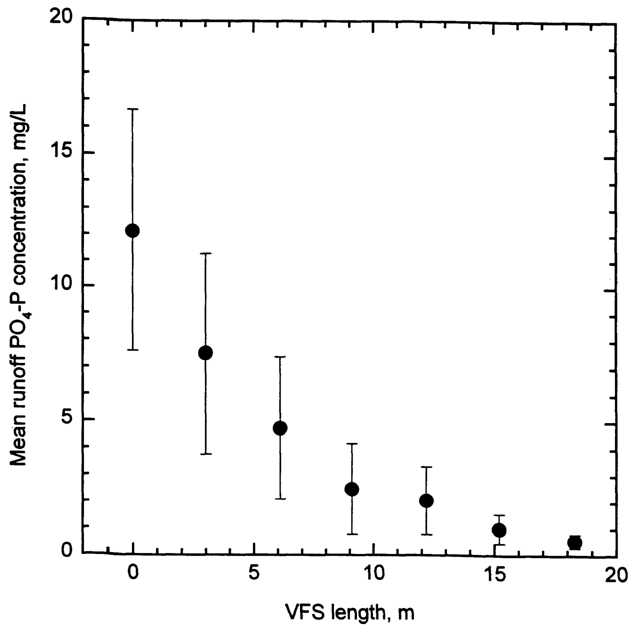

Figure 5–Effect of vegetative filter strip (VFS) length on runoff orthophosphorus (PO_4-P) concentration. Filled circles indicate means, and total bar length is two standard deviations.

that for NO_3-N, TKN and TOC, concentrations in runoff did not decrease significantly beyond VFS lengths of 3 m. For NH_3-N, PO_4-P and TP, runoff concentrations decreased up to a VFS length of 6 m, beyond which no significant reductions occurred.

The lack of a significant VFS length effect on TSS concentrations might have been due in part to the relatively low runoff concentrations. Many studies have indicated that VFS are effective in removing solids from incoming runoff (e.g., Edwards et al., 1983; Dillaha et al., 1989; Mickelson and Baker, 1993). These reports, however, involved pollutant sources capable of generating high runoff TSS concentrations (e.g., row-cropped pollutant source area). In comparison to more intensively-managed pollutant sources, TSS concentrations in runoff from these plots were quite small. The concentration of TSS in runoff entering the VFS, averaged over all treatments and replications, was only 85 mg/L. This is in comparison to, for example, the average of approximately 8500 mg/L reported by Mickelson and Baker (1993). In this case, the generation of TSS within the VFS was not dominated by incoming sediment, and TSS concentrations measured

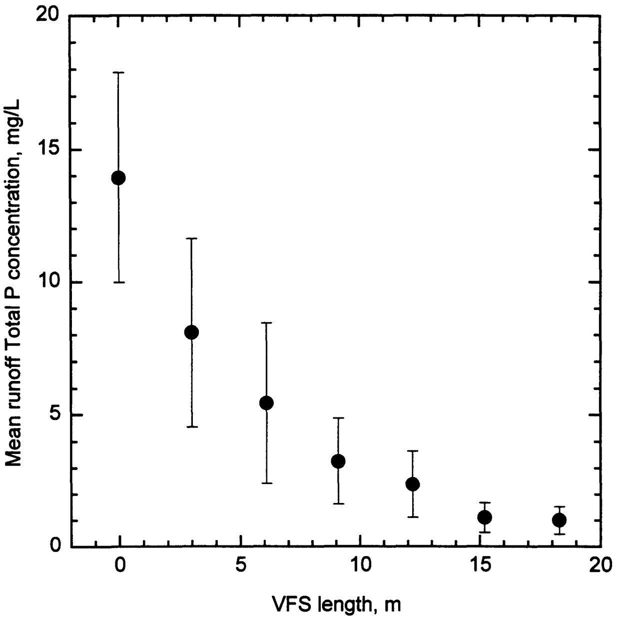

Figure 6–Effect of vegetative filter strip (VFS) length on runoff total phosphorus (P) concentration. Filled circles indicate means, and total bar length is two standard deviations.

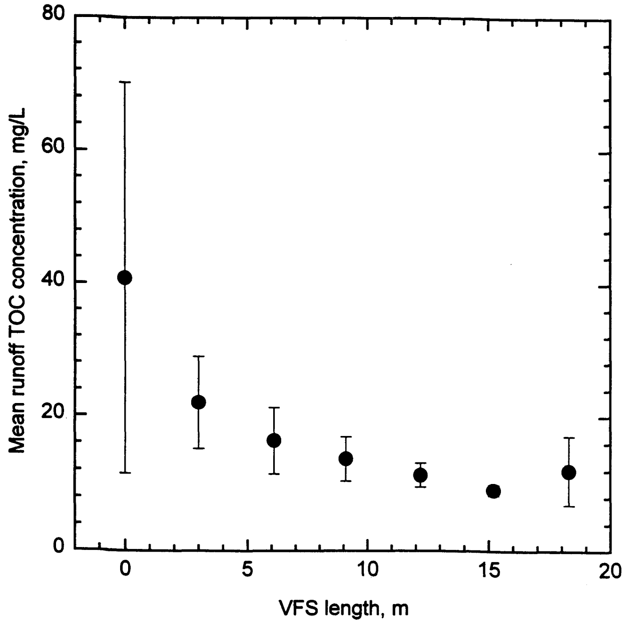

Figure 7–Effect of vegetative filter strip (VFS) length on runoff total organic carbon (TOC) concentration. Filled circles indicate means, and total bar length is two standard deviations.

within the VFS were thus more sensitive to localized irregularities that promoted solids loss in the VFS.

The mean (geometric) runoff concentration of FC was 1.3 × 10^6 colony-forming units/100 mL, averaged over all treatments and replications. Why FC concentrations did not respond to VFS length is unclear, particularly since others (e.g., Coyne and Blevins, 1995) working with similar experimental situations have reported FC concentration reductions attributable to VFS. The lack of a VFS length effect on runoff FC concentration might have been due to relatively high background FC concentrations within the VFS, but additional work would be necessary to verify the reason(s) for this unexpected finding.

POLLUTANT MASS TRANSPORT

Mass transport of NH_3-N, TKN, PO_4-P, TP, and TOC were significantly ($p < 0.06$) influenced by litter-treated length (table 6). Even though runoff concentrations of these pollutants exiting the litter-treated areas did not differ significantly, runoff exiting the litter-treated areas increased with length of treated area, thereby increasing the product of concentration and runoff volume. Transport of TSS and NO_3-N, on the other hand, was unaffected by length of litter treatment. There is no physical reason why transport of NO_3-N and TSS should not have increased with litter-treated length. Indeed, the data suggest this trend, even though it was not statistically significant. The likely explanation for the lack of a litter-treated length effect on NO_3-N and TSS transport is high variability in runoff concentrations of these pollutants (relative to the other pollutants investigated), possibly promoted by the low magnitudes of those concentrations.

Vegetative filter strip length had no significant effect on mass transport of any pollutant investigated. This finding was a mild surprise but not altogether unexpected, since it is typically more difficult to detect differences in mean mass transport values than differences in concentration values. This is because mass transport is computed as the product of two variables (runoff and concentration) and will generally have a higher variance than either of these two variables alone. Using NH_3-N as an example, one may consider the one standard deviation error bars given in figure 3 and the standard deviations of plot runoff amounts give in table 5, and then compare these measures of variability to those given in figure 8. Figure 8 demonstrates quite high variability in mass transport and, even though no statistically significant VFS length effect was detected, a clearly decreasing trend in mass transport with increasing VFS length. Thus, it could be a mistake to conclude that the concentration reductions reported earlier are due merely to dilution and that no actual mass removal is occurring within the VFS, because assessing VFS performance in terms of mass transport is impacted by plot-to-plot variability in runoff amounts as well as by actual mass removal.

Mass transport of NO_3-N and TSS, averaged over all treatments and replications, was 0.51 and 76.4 g with standard deviations of 0.35 and 47.9 g, respectively.

Table 5. Plot runoff depths

Litter-treated Length (m)	Replication	Runoff Depth (mm)
6.1	1	25.2
	2	13.2
	3	6.0
12.2	1	29.9
	2	21.4
	3	20.0
18.3	1	25.2
	2	9.6
	3	18.6
Mean		18.8
Standard deviation		7.9

Table 6. Masses (g) of pollutants entering and exiting VFS

Pollutant	Litter-treated Length/VFS Length					
	6.1 m/18.3 m		12.2 m/12.2 m		18.3 m/6.1 m	
	Entering	Exiting	Entering	Exiting	Entering	Exiting
NH_3-N						
Mean*	4.4	0.6	9.5	3.9	13.0	9.6
SD†	3.6	0.8	4.5	2.6	10.3	10.0
TKN						
Mean	8.9	1.9	18.6	7.8	21.6	13.9
SD	7.6	2.0	10.0	5.0	15.9	12.0
PO_4-P						
Mean	2.1	0.4	4.9	2.8	6.7	4.8
SD	2.4	0.4	2.5	1.4	4.5	4.3
TP						
Mean	2.3	0.7	5.6	2.9	7.5	5.6
SD	2.0	0.7	2.1	1.4	4.9	4.8
TOC						
Mean	11.1	4.9	12.9	10.9	16.6	13.8
SD	13.9	3.7	3.5	2.7	10.8	9.6

* Mean of three replications.
† Standard deviation.

POLLUTANT MASS REMOVAL EFFECTIVENESS

Vegetative filter strip effectiveness in removing pollutant mass was calculated for NH_3-N, TKN, PO_4-P, TP, and TOC using the equation:

$$E_{i,j} = 100\left(\frac{M_{i,o} - M_{i,j}}{M_{i,o}}\right) \quad (1)$$

where $E_{i,j}$ is the effectiveness (%) of VFS length j for pollutant i, $M_{i,j}$ is the mass of pollutant i transported past VFS length j, and $M_{i,o}$ is the mass of pollutant i entering the VFS. These calculations were performed in an attempt to find a VFS performance criterion that was not as sensitive to runoff volume as mass transport alone, even though VFS length did not have a significant effect on mass transport. Mass removal effectiveness was not calculated for NO_3-N or TSS since neither concentrations nor mass transport of these pollutants depended on litter-treated or VFS length.

Analysis of the calculated mass removal effectiveness values produced mixed results. Mass removal effectiveness for VFS lengths up to 6.1 m depended on the contributing litter-treated length, except in the case of PO_4-P, with the highest effectiveness associated with the shortest litter-treated length. This finding likely reflects the role of overland flow hydraulics with respect to VFS performance. In this study, incoming pollutant concentrations were the same irrespective of litter-treated length, but the incoming masses of pollutants (with exceptions as noted earlier) increased with litter-treated length due to increased runoff. The amount of pollutants infiltrating within the VFS is generally limited by soil hydraulic characteristics and thus will not differ markedly with the amount of runoff across the VFS. Assuming infiltration to be a significant mechanism of pollutant mass removal (if not the most important, in this situation), proportionately less pollutant mass removal should occur as mass loading is increased through increased runoff with a constant pollutant concentration.

Length of the VFS significantly affected mass transport removal effectiveness for NH_3-N, TKN, PO_4-P, TP, and TOC. With the exception of PO_4-P, however, these effects were significant only for litter-treated lengths of 12.2 and/or 18.3 m. Removal effectiveness with respect to PO_4-P did not vary with litter-treated length. Figures 9 through 13 depict the relationship between pollutant mass

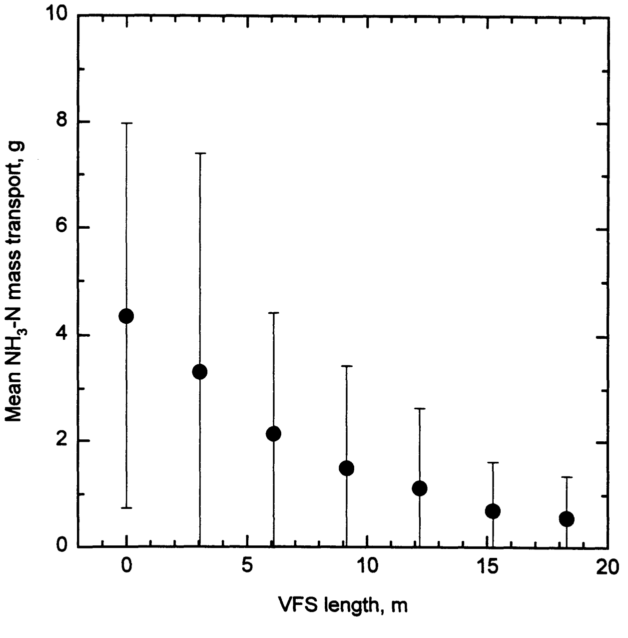

Figure 8–Trend in runoff ammonia nitrogen (NH_3-N) transport vs. vegetative filter strip (VFS) length for 6.1 m litter-treated length. Filled circles indicate means, and total bar length is two standard deviations. Runoff NH_3-N transport was not significantly ($p > 0.05$) affected by VFS length according to analysis of variance.

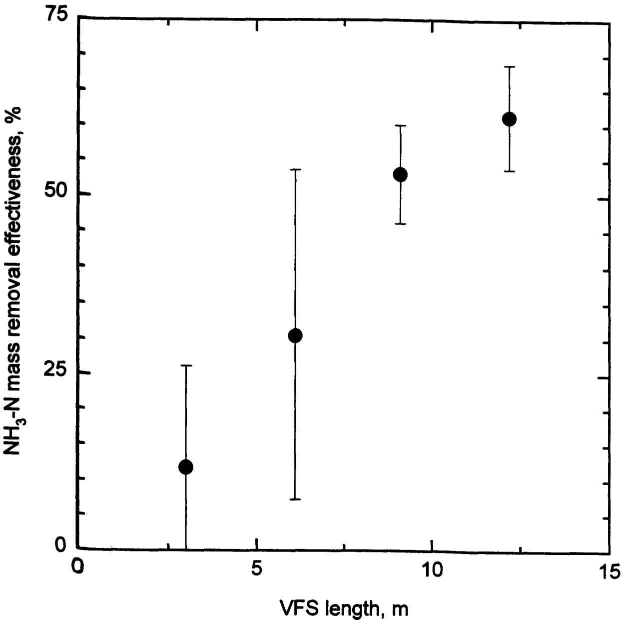

Figure 9–Effect of vegetative filter strip (VFS) length on ammonia nitrogen (NH_3-N) mass removal effectiveness. Filled circles indicate means, and total bar length is two standard deviations. Data shown are for a litter-treated length of 12.2 m.

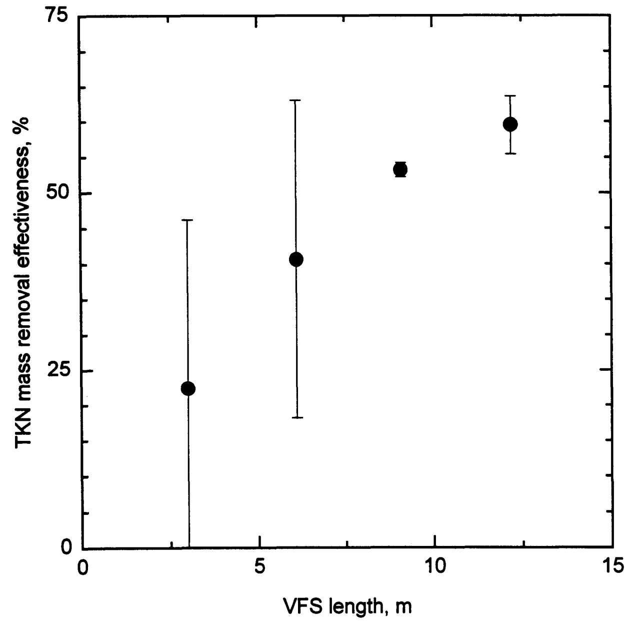

Figure 10–Effect of vegetative filter strip (VFS) length on total Kjeldahl nitrogen (TKN) mass removal effectiveness. Filled circles indicate means, and total bar length is two standard deviations. Data shown are for a litter-treated length of 12.2 m.

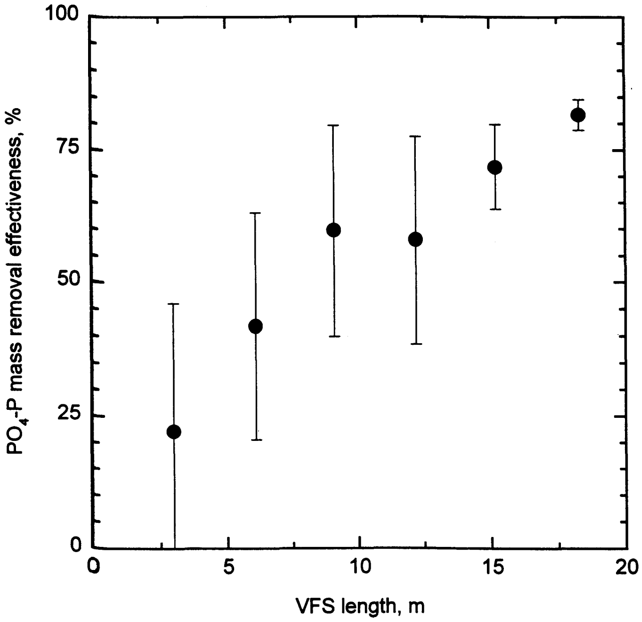

Figure 11–Effect of vegetative filter strip (VFS) length on orthophosphorus (PO_4-P) mass removal effectiveness. Filled circles indicate means, and total bar length is two standard deviations. Data shown are averaged across all litter-treated lengths.

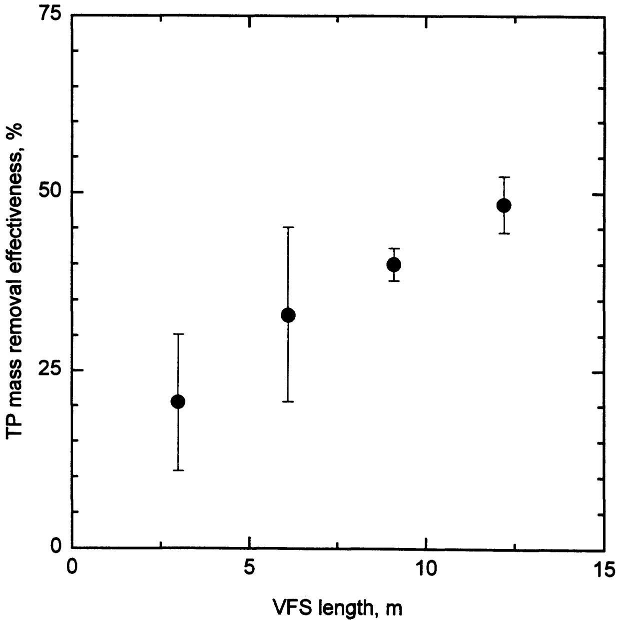

Figure 12–Effect of vegetative filter strip (VFS) length on total phosphorus (P) mass removal effectiveness. Filled circles indicate means, and total bar length is two standard deviations. Data shown are averaged across 12.2 and 18.3 m litter-treated lengths.

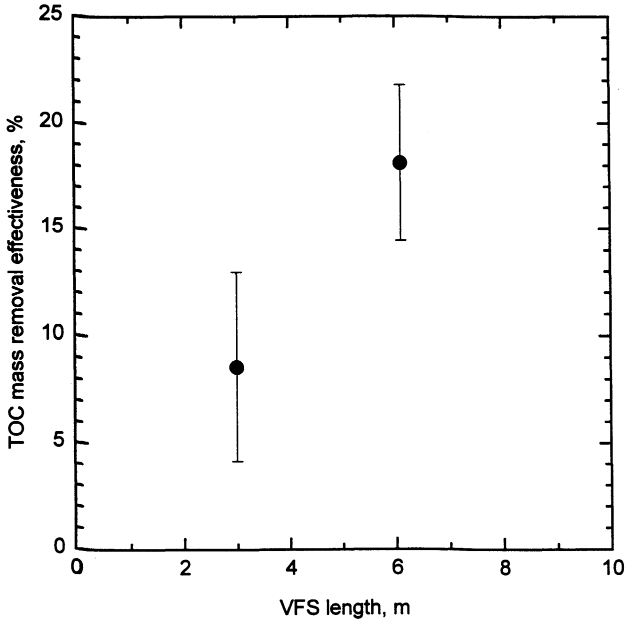

Figure 13–Effect of vegetative filter strip (VFS) length on total organic carbon (TOC) mass removal effectiveness. Filled circles indicate means, and total bar length is two standard deviations. Data shown are for a litter-treated length of 18.3 m.

removal effectiveness and VFS length for NH_3-N, TKN, PO_4-P, TP, and TOC, respectively, in the cases where effectiveness was significantly affected by VFS length. Effectiveness values in these figures are averaged across one or more litter-treated length as indicated in the captions, because means testing indicated no significant differences in effectiveness attributable to litter-treated length. Mean effectiveness values are reported in table 7 for cases in which effectiveness was not dependent on VFS length.

The lack of a VFS length effect on mass removal effectiveness for the 6.1 m litter-treated length is likely due to the small incoming pollutant load relative to the VFS lengths studied. In other words, the majority of mass removal in the 18.3 m VFS occurred prior to a VFS length of 3 m. Had smaller VFS length increments been examined, a significant effect might have been detected. The cause of the differing results with respect to the 12.2 and 18.3 m litter-treated lengths is not apparent, but could

Table 7. Mass removal effectiveness of VFS

Pollutant	Litter-treated Length (m)	Maximum VFS Length (m)	Mass Removal Effectiveness Mean* (%)	Mass Removal Effectiveness SD† (%)
NH_3-N	6.1	18.3	75.0	25.4
	12.2‡	12.2	39.2	23.8
	18.3	6.1	27.0	16.0
TKN	6.1	18.3	67.2	19.7
	12.2‡	12.2	43.9	20.5
	18.3	6.1	21.4	21.8
TP	6.1	18.3	65.5	16.9
	12.2‡	12.2	36.0	11.9
	18.3‡	6.1	25.5	14.5
TOC	6.1	18.3	30.3	33.6
	12.2	12.2	10.9	8.3
	18.3‡	6.1	13.3	6.4

* Mean of three replications.

† Standard deviation.

‡ Mass removal effectiveness was a function of VFS length, as given in figures 9-13. Statistics reported are for all VFS lengths.

be related to the hydraulics (soil and runoff) involved as well as the relative roles of the specific filtering mechanisms that are operative for the various pollutants.

SUMMARY AND CONCLUSIONS

This study assessed the influences of litter-treated length and VFS length on performance of VFS with regard to removing pollutants from runoff originating from grassed areas treated with poultry litter. Litter-treated lengths of 6.1, 12.2, and 18.3 m were used with corresponding VFS lengths of up to 18.3, 12.2, and 6.1 m, respectively. Simulated rainfall was applied at 50 mm/h for 1 h of runoff to generate runoff samples, which were subsequently analyzed for nutrients, organic carbon, solids, and fecal coliforms. The study produced several findings that can be helpful from the standpoints of designing VFS and conducting future research on VFS performance.

Pollutant concentrations in runoff exiting the litter-treated area in no case depended on the litter-treated length, suggesting the occurrence of a relatively rapid equilibrium. Although this result is probably not directly applicable to cases with significantly different soils, runoff amounts and related variables, it does suggest that the task of estimating incoming pollutant concentrations for various manure-treated lengths might be simplified. Mass loading to the VFS, on the other hand, depended on litter-treated length, since the runoff volumes increased with increasing litter-treated length.

Pollutant concentrations decreased with increasing VFS length for all pollutants studied, but mass transport was not affected by VFS length. In itself, this result suggests that the concentration reductions were due merely to dilution. The trends in the data as well as the inherently higher variability in mass transport relative to concentration or runoff alone, however, suggest that high runoff variability might have masked mass removal by the VFS.

Mass removal effectiveness of the VFS generally decreased with increasing litter-treated length (i.e., with increased pollutant loading). This finding indicates a limiting factor within the VFS, most likely the infiltration rate in this case. The mass removal effectiveness of the VFS generally increased with increasing VFS length for litter-treated lengths of 12.2 and/or 18.3 m. The lack of a significant VFS effect on mass removal effectiveness at the 6.1 m litter-treated length (having the least pollutant loading to the VFS) indicates that a relatively large proportion of mass removal had occurred prior to a VFS length of 3 m. A VFS effect on mass removal effectiveness would likely have been detected had shorter VFS lengths been studied.

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