Major Factors Influencing the Efficacy of Vegetated Buffers on Sediment Trapping: A Review and Analysis

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Sediment is a major agricultural pollutant threatening water quality. Vegetated buffers, including vegetative filter strips, riparian buffers, and grassed waterways, are best management practices (BMPs) installed in many areas to filter sediments from tailwaters, and deter sediment transport to water bodies. Along with reducing sediment transport, the filters also help trap sediment bound nutrients and pesticides. The objectives of this study were: (i) to review vegetated buffer efficacy on sediment trapping, and (ii) to develop statistical models to investigate the major factors influencing sediment trapping. A range of sediment trapping efficacies was found in a review of over 80 representative BMP experiments. A synthesis of the literature regarding the effects of vegetated buffers on sediment trapping is needed. The meta-analysis results based on the limited data showed that buffer width and slope are two major factors influencing BMPs efficacy of vegetated buffers on sediment trapping. Regardless of the area ratio of buffer to agricultural field, a 10 m buffer and a 9% slope optimized the sediment trapping capability of vegetated buffers.

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Sediment continues to be a major nonpoint source of pollution for surface waters worldwide. It can affect stream habitat and water quality by reducing water clarity for sighted organisms, and reducing light penetration for plant growth. Aesthetic appeal is also reduced by the presence of suspended sediments. Sediments, which settle on the substrate, fill interstitial spaces and affect the habitat available for invertebrates (Ryan, 1991). Chemicals and pathogens can be transported in surface runoff attached to sediment, contributing to deterioration of water quality (Munoz-Carpena and Parsons, 2004). For example, sediment in surface runoff can carry particulate forms of phosphorus (P), and a high proportion of total P loading has been found to occur during periods of high flow (Culley and Bolton, 1983; Smith, 1987). A review paper by Laskowski (2002) indicated that the partition coefficients between water and soil media (Koc) of pyrethroid compounds range from 10^5 to about 7×10^5. The physiochemical properties of pyrethroids reflect a strong tendency to be adsorbed to suspended organic carbons, and therefore, to potentially move off-site attached to sediment (Bacey et al., 2005).

Best management practices (BMPs) such as grassed buffer strips, including vegetative filter strips, riparian buffer zones, and grass waterways, adjacent to source areas have been suggested as potential controls to help reduce erosion and offsite transport of sediment. Vegetated buffers are defined areas of vegetation designed to remove sediment and other pollutants from surface water runoff by filtration, deposition, and infiltration (Dillaha et al., 1989). Buffer vegetation, especially grass, acts as a filter by increasing surface roughness, which augments infiltration by decreasing flow volumes and velocity (Borin et al., 2005). The filter thus enhances sediment deposition and filtration by vegetation, pollutant adsorption onto soil and plant materials, and uptake of soluble pollutants by plants (Misra et al., 1996; Blanche et al., 2003). The efficacy of vegetated buffers in erosion control and the control of pollutants has already been the subject of numerous studies, which generally show a positive effect on reducing the transfer of sediments, nutrients, and pesticides to surface waters (Patty et al., 1997; Aora et al., 2003).

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Abbreviations: BMPs, best management practices; P, phosphorus; NRCS, Natural Resources Conservation Service; USLE, universal soil loss equation; VFS, vegetated filter strips.

Often, vegetated buffers are defined operationally as the zone of vegetation adjacent to streams, rivers, creeks, or wetlands (Lee et al., 2004). For this paper, vegetated filter strips, riparian buffer zone, and grassed waterways are terms used synonymously. The terms "width" and "length" were used to describe the dimension of the buffers, depending on the shape of the buffer. In any case, they were used to refer to the travel distance of the runoff flow. Therefore, this review uses width for both cases.

BMP effects of vegetated buffers depend on external factors including, but not limited to, buffer width, slope, area ratio of buffer to source field, vegetation species, soil texture, and flow velocity. Buffer width is the most studied factor. It has been reported that the extent to which riparian buffers attenuate nitrogen and improve stream water quality is thought to be a partial function of buffer width (Vidon and Hill, 2004), and by some estimates, account for 81% of a buffer's nitrogen removal efficacy (Phillips, 1989). Experimental investigation by Abu-Zreig et al. (2004) found that the buffer width is the predominant external factor affecting sediment deposition.

Some reviews or summary reports on the efficacy of vegetated buffers for reducing nutrients (Mayer et al., 2005; Mayer et al., 2007) and pesticides (Schulz, 2004; Krutz et al., 2005; Reichenberger et al., 2007) have been published. However, a comprehensive literature review on the efficacy of vegetated buffers for reducing sediment does not exist. The objectives of this paper were to give a summary of BMP effects of vegetated buffers for attenuating sediments, develop statistical models to determine sediment trapping efficacy by varying buffer width, slope, and area ratio parameters based on the dataset collected from the literature, and determine an optimal width and slope for vegetated buffers to reduce sediment transport. Through a summary and analysis of the data collected from the literature, the results would be expected to be beneficial to future vegetated buffer construction for sediment and insecticide attenuation, and other related research.

Materials and Methods

Various databases were used when we searched literature on vegetated buffer and sediment trapping efficacy. The key words sediment, buffer, vegetated ditches, riparian, grass waterways, filter strip, constructed wetland, etc., were used alone or a combination in the search. We categorized the searched literature based on the different types of buffer. Detailed information on authors, journal, location, soil, rainfall, buffer width, buffer slope, area ratio, and percent sediment trapping, etc. were recorded while we reviewed each of the papers.

Mass sediment attenuated in the buffer is the key parameter in assessing performance in improving water quality. Dosskey et al. (2006) conducted a VFSMOD study and indicated that the mass sediment reduction is a key factor affecting sediment trapping efficacy. Therefore, Table 1 also shows sediment inflow, outflow, and mass sediment reduction data.

Box plots were used in this study to represent the efficacy of each of the buffers for sediment trapping. Box plots are pictorial representations of the distribution of values of a variable. The central line in each box marks the median value and the edges of the box mark the first and third quartiles. The median value of a distribution is the 50th percentile, which is the value that divides the observations so that at least half are less than or equal in value to the median value, and at least half are equal to or greater in value than the median. The first and third quartiles are the 25th and 75th percentiles.

We used backward stepwise regression analysis to select the main factors affecting sediment trapping efficacy. Sediment inflow, outflow, and mass sediment reduction are also included in Table 1. Nonlinear regression models were fitted to the data to reveal patterns of percent sediment removal and buffer width and buffer slope, respectively. All analysis and model fitting were performed with SAS 9.1.2.

Theoretical Framework

Buffer Function

Vegetated buffers can protect adjacent wildlife habitat, wetlands, and water bodies from harmful human activities. A vegetated buffer of the proper width can effectively intercept sediments and reduce nutrient load and other nonpoint source pollutants from surface runoff (Lowrance et al., 1984, 1986; Peterjohn and Correll, 1984; Pinay and Decamps, 1988). Vegetated buffers serve to prevent erosion of soil through soil stabilization. Maintenance of vegetated buffer strips and reduction of erosion lowers the potential for particulate movement by surface runoff, thereby reducing the potential for water quality degradation (Herricks and Osborne, 1985). Buffers can enhance landscape diversity and increase wildlife habitat by providing more forage sites, additional nesting and breeding areas, and by serving as migration corridors.

Factors Controlling Sediment Retention

Vegetated buffer functions are affected by many factors including soil, buffer width, flow rate, rainfall intensity, slope, area ratio of buffer to source field, vegetation type, and relative height of water to plants. A detailed description of these factors is presented below.

Soil

Vegetated buffers capture sediment and organic material by decreasing the velocity of runoff water. As agricultural runoff passes through a buffer at the field edge or within the field, vegetation slows down the flow velocity, which provides time for the water to infiltrate, and then percolate into the soil profile. As a result, sediment and other suspended materials settle out of the runoff. This process is largely affected by the size of the soil particles. As water is slowed, larger soil and organic particles rapidly settle out of suspension. Smaller clay particles need a lower energy level and more time within the filter to settle. Gharabaghi et al. (2006) found that almost all of the easily removable particles (larger than 40 microns in diameter) were captured with the first few meters of the filter strip. However, the remaining small size particles were very difficult to remove by filtering due to their tendency to stay in suspension. The only mechanism that helped in the removal of small size sediments was water infiltration. During experimental runs with low to

Table 1. Summary of buffer characteristics and their separate trapping efficacy in sediment.

Paper source	BMP	Location	Buffer width	Area ratio	Slope	Sediment trapping efficacy	Inflow	Outflow	Mass sediment reduction
			m	buffer/plot	——%——		——kg——		
Young et al. (1980)	VFS†		4.06	0.028	4	79	35.37	6.4	28.97
Hall et al. (1983)	VFS	Pennsylvania	6	0.27	14	76	0.000008	0.000002	0.000006
Hayes and Hairston (1983)	VFS	Mississippi	2.6		2.35	60			
Dillaha et al. (1989)	VFS	Virginia	9.1	0.5	11	97.5			
	VFS	Virginia	4.6	0.25	11	86			
	VFS	Virginia	9.1	0.5	16	70.5			
	VFS	Virginia	4.6	0.25	16	53.5			
	VFS	Virginia	9.1	0.5	5	93			
	VFS	Virginia	4.6	0.25	5	83.5			
Magette et al. (1989)	VFS	Maryland	9.2	0.42	2.7	92.4	70.8	5.4	65.4
	VFS	Maryland	4.6	0.21	2.7	82.8	70.8	12.2	58.6
	VFS	Maryland	9.2	0.42	2.7	88.3	16.2	1.9	14.3
	VFS	Maryland	4.6	0.21	2.7	64.3	16.2	4.97	11.23
	VFS	Maryland	9.2	0.42	4.1	80.3	13.6	2.68	10.92
	VFS	Maryland	4.6	0.21	4.1	65.8	13.6	4.65	8.95
Parsons et al. (1990)	VFS	North Carolina	4.3	0.12	3.25	75			
	VFS	North Carolina	8.5	0.23	3.25	85			
Parsons et al. (1994)	VFS	North Carolina	4.3	0.12	1.9	78			
	VFS	North Carolina	8.5	0.23	1.9	81			
Coyne et al. (1995)	VFS	Kentucky	4.6	0.4	9	99	0.014	0.002	0.012
Arora et al. (1996)	VFS	Iowa	20.12	0.033	3	83.6			
	VFS	Iowa	20.12	0.067	3	87.6			
Daniels and Gilliam (1996)	VFS	North Carolina	3	0.034	4.9	59			
	VFS	North Carolina	6	0.071	4.9	61			
	VFS	North Carolina	3	0.034	2.1	45			
	VFS	North Carolina	6	0.071	2.1	57			
Robinson et al. (1996)	VFS	Iowa	3	0.05	7	70			
	VFS	Iowa	3	0.05	12	80			
	VFS	Iowa	9.1	0.15	12	85			
	VFS	Iowa	9.1	0.15	7	85			
Van Dijk et al. (1996)	VFS	Netherlands	1		5.2	49.5			
	VFS	Netherlands	4		5.2	78.5			
	VFS	Netherlands	5		2.3	73			
	VFS	Netherlands	10		2.3	94			
	VFS	Netherlands	5		2.5	64.5			
	VFS	Netherlands	10		2.5	99			
	VFS	Netherlands	5		8.5	92			
	VFS	Netherlands	10		8.5	97.5			
Patty et al. (1997)	VFS	Brittan, France	6	0.12	7	98.9	493.2	5.44	487.76
	VFS	Brittan, France	12	0.24	7	99	493.2	3.7	489.5
	VFS	Brittan, France	18	0.36	7	99.9	493.2	0.37	492.83
	VFS	Brittan, France	6	0.12	10	87	20.4	2.53	17.87
	VFS	Brittan, France	12	0.24	10	100	20.4	0	20.4
	VFS	Brittan, France	18	0.36	10	100	20.4	0	20.4
	VFS	Brittan, France	6	0.12	15	91	309.16	28.71	280.45
	VFS	Brittan, France	12	0.24	15	97	309.16	8.21	300.95
	VFS	Brittan, France	18	0.36	10	98	309.16	4.8	304.36
Barfield et al. (1998)	VFS	Kentucky	4.57	0.21	9	97	258	8.44	249.56
	VFS	Kentucky	9.14	0.41	9	99.9	212	1.1	210.9
	VFS	Kentucky	13.72	0.62	9	99.7	361	2.06	358.94
Coyne et al. (1998)	VFS	Kentucky	9	0.41	9	99			
	VFS	Kentucky	4.5	0.24	9	95			
	VFS	Kentucky	9	0.67	9	98			
Tingle et al. (1998)	VFS	Mississippi	0.5	0.018	3	88	0.018	0.0022	0.0158
	VFS	Mississippi	1	0.045	3	93	0.036	0.0024	0.0336
	VFS	Mississippi	2	0.09	3	94	0.072	0.004	0.068
	VFS	Mississippi	3	0.14	3	96	0.108	0.0048	0.1032
	VFS	Mississippi	4	0.18	3	98	0.144	0.0032	0.1408
Munoz-Carpena et al. (1999)	VFS	North Carolina	4.3	0.11	6	86	64.76	1.74	63.02
	VFS	North Carolina	8.5	0.22	6	93	54.88	3.99	50.89
Schmitt et al. (1999)	VFS	Nebraska	7.5	0.093	6.5	85	3.99	1.3	2.69

(cont'd)

Table 1. Continued.

Paper source	BMP	Location	Buffer width	Area ratio	Slope	Sediment trapping efficacy	Inflow	Outflow	Mass sediment reduction
			m	buffer/plot	%		kg		
	VFS	Nebraska	15	0.19	6.5	96	3.01	0.84	2.17
Sheridan et al. (1999)	VFS	Georgia	8	0.03	2.5	81			
Lee et al. (2000)	VFS	Iowa	7.1	0.32	5	70	2.82	0.85	1.97
Abu-Zreig et al. (2004)	VFS	Canada	2	0.2	2.3	68	5887	1876	4011
	VFS	Canada	15	0.025	2.3	98	9324	219	9105
Blanco-Canqui et al. (2004)	VFS	Columbia, MO	8	0.09	5	90	$1.6*10^{-8}$	$1.3*10^{-10}$	$1.58*10^{-8}$
Borin et al. (2005)	VFS	North-east, Italy	6		1.8	94	3450	200	3250
Helmers et al. (2005)	VFS	Nebraska	13	0.06	1	80	147	29	118
Gharabaghi et al. (2006)	VFS	Ontario, Canada	2.5			50			
	VFS	Ontario, Canada	20			98			
Young et al., (1980)	Riparian buffer		21.3		4	78			
	Riparian buffer		27.4		4	79			
Peterjohn and Correll (1984)	Riparian buffer	Maryland	19		5	90			
	Riparian buffer	Maryland	60		5	94	3.99	1.3	2.69
Dillaha et al. (1988)	Riparian buffer		4.6		11	87			
	Riparian buffer		4.6		16	76			
	Riparian buffer		9.1		11	95			
	Riparian buffer		9.1		16	88			
Dillaha et al. (1989)	Riparian buffer		4.6		11	86	$0.1*10^{-6}$	$0.2*10^{-7}$	$0.8*10^{-7}$
	Riparian buffer		4.6		16	53	$2.3*10^{-7}$	$1.1*10^{-7}$	$1.2*10^{-7}$
	Riparian buffer		9.1		11	98	$2*10^{-7}$	$0.1*10^{-7}$	$1.9*10^{-7}$
	Riparian buffer		9.1		16	70	$4.5*10^{-7}$	$1.4*10^{-7}$	$3.1*10^{-7}$
Fiener and Auerswald (2003)	Grassed waterways	Munich	35	0.16	9.3	97	330.72	7.42	323.3
	Grassed waterways	Munich	17.5	0.12	9	77	175.74	40.02	135.72
Fiener and Auerswald (2005)	Grassed waterways	Central Europe	18.5	0.076	3.6	93			

† VFS represents vegetated filter strips.

moderate flow rates on longer plot lengths (20 m wide filter strips), 90% removal efficacy of sediment could be achieved because fine sediments were able to infiltrate into the soil with water.

Buffer Width

Buffer width is one of the most important factors influencing sediment trapping. As stated before, a larger buffer strip width is essential for the removal of fine-grained soil particles. Buffer strips work best when the overland runoff flow is shallow and uniform within the buffer (Barfield et al., 1979). If water becomes concentrated into small channels, the efficacy of the strip is drastically reduced.

Under-sized buffers provide inadequate protection for water bodies. Over-sized buffers remove land from production, which may result in economic losses. However, a universal optimum width for buffers does not exist due to the wide range of variables governing the efficacy of the vegetated buffers. Filter width should be wide enough to effectively trap clay-sized particles which require the lowest flow velocities through the filters.

Area Ratio

Many of the studies had big buffer area to source area ratios, often well below the value expected in typical applications. An area ratio greater than 1:20 may be expected under most field conditions. Of the studies reported, 50% had an area ratio greater than 1:5 (Helmers et al., 2005). The Natural Resources Conservation Service (NRCS) sets standards for buffer width based on universal soil loss equation (USLE) *R* factor values (rainfall amount and intensity). The recommendations are that the ratio of the filter strip area to the source area be greater than 1:70 in regions with USLE *R* factor values between 0 and 35, 1:60 in regions with *R* factor values between 35 and 175, and 1:50 in regions with *R* factor values more than 175. Arora et al. (1996) investigated the relationship between the area of the vegetative filter strip and the area of the drainage plot discharging to a vegetative filter strip. The term "area ratio" represents this relationship. Ratios of 1:15 and 1:30 were evaluated for their impact on the reduction of three moderately adsorbed herbicides from agricultural activities. Higher area-ratio buffers (those with greater filter strips to drainage area) resulted in higher sediment trapping efficacy and thus increased the reduction of herbicide and phosphorus load.

Flow

Most of the research on vegetated buffers assumes that the flow of runoff is laminar across the buffer. However, in reality, natural berms often develop along field edges from deposition of sediment and, in result, create concentrated flows. The efficacy of buffers is reduced dramatically by concentrated flow because of increased velocity. This failure of real world scenarios to meet the conditions and assumptions of experiments causes difficulty in applying research results on buffer efficacy to guide field implementation. An early study by Dillaha et al. (1986) sampled a number of grass filter strips that had been constructed under the Conservation Reserve program, which paid landowners to remove land from agricultural production and replace it with perennial buffers. This study found that the majority of buffers would be ineffective under concentrated flow conditions. Therefore, to maintain peak efficacy, it is essential to maintain sheet flow where runoff enters into edge-of-field buffers.

Buffer Slope

Buffer slope is another key factor in determining sediment trapping efficacy (Young et al., 1980; Peterjohn and Correll, 1984; Dillaha et al., 1989; Magette et al., 1989; Phillips, 1989). More steeply sloped fields may produce faster runoff and thus reduce a buffer's efficacy in trapping pollutants. Among the literature reviewed, buffer slope varied from 2% (Daniels and Gilliam, 1996; Van Dijk et al., 1996) to as high as 16% (Dillaha et al., 1989). Research in Indiana, Virginia, Maryland, and Iowa has shown that for slopes ranging from 3 to 12% buffer strips can remove 56 to 97% of sediment, depending on buffer width and the area draining to the buffer strip (Franti, 1997). Removal rates are best with shallow, uniform flow across the filter and relatively small drainage areas. Actual field removal rates will depend on many factors and will likely be less than experimental rates.

Rainfall Intensity

The rainfall intensity and antecedent moisture determine how much runoff the buffer can capture during a runoff event. Effectiveness of the buffer is low when the soil is saturated before the runoff event. During frequent rainfall events, soils in the vegetated buffers are saturated with water and infiltration rate is very low. Under these conditions, the buffers are not effective in reducing sediment runoff.

Vegetation

The height of vegetation in the buffers relative to runoff water depth is another important factor. When the depth of runoff water moving through the filter is greater than the height of the vegetation in the filter, vegetation orientation becomes parallel with overland flow. The rate of flow through the filter increases, which decreases the amount of sediment that settles from the water column. Recently, stiff-stemmed grass species have received much attention for their use as narrow hedges. Studies suggest that switchgrass barriers used in combination with fescue vegetative filter strips can improve the conservation effectiveness of the buffers (Blanco-Canqui et al., 2004).

Results and Discussion

General Efficacy

Table 1 summarizes the literature discussing vegetated buffers. Some important parameters such as buffer width, area ratio of buffer to agricultural field and slope for vegetative filter strips, riparian buffer zones, and grassed waterways are included in this table. The soil textures in these studies were mostly silt loam. Vegetated buffer BMPs in the studies exhibited an excellent potential for sediment removal, with an efficacy ranging from 45 to 100%.

Box plots are presented in Fig. 1 to visually represent the efficacy of each of the three types of vegetated buffer BMPs for sediment trapping. Grassed waterways exhibited a very high efficacy for sediment trapping. However, only three case studies of grassed waterways were found and included in this review. The vegetated filter strips and riparian buffers also produced significant sediment trapping in the cases studied. The median trapping efficacy value

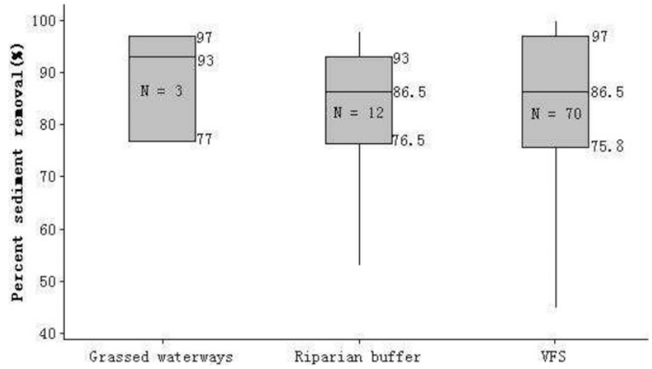

Fig. 1. Box Plots of sediment trapping efficacy by different BMPs (grassed waterways, riparian buffer, and VFS: vegetated filter strips).

for the vegetated filter strips was the same as the median value for the riparian buffer. However, the variance for the results of the vegetated filter strip studies was larger than the variance of the riparian buffer data. Each method shows potential for successful use in reducing sediment transport, and therefore may be useful for trapping hydrophobic insecticides and other sediment-attached chemicals such as phosphorus. One vegetated buffer might be chosen over another depending on site-specific conditions and needs.

Statistical Analysis

Based on the limited data obtained from the literature review, the relationship between sediment trapping efficacy, and buffer width and slope was analyzed, respectively.

Buffer Width and Sediment Trapping Efficacy

Figure 2 shows that the relationship between buffer width and sediment trapping is described by a logarithmic regression model ($R^2 = 0.34$, $P < 0.001$). With increasing buffer width sediment trapping efficacy is improved. However, the cost of buffer construction and maintenance also increases with width. The costs of applying inappropriate design widths are not trivial. Under-sized buffers provide inadequate protection for water bodies. Oversized buffers remove land from production unnecessarily (Dillaha and Inamdar, 1997). In addition, cost estimates for construction and maintenance are needed. Little data are available on the actual construction costs of vegetated buffers. One rough estimate can be the cost of seed or sod, which is approximately $3.20 per

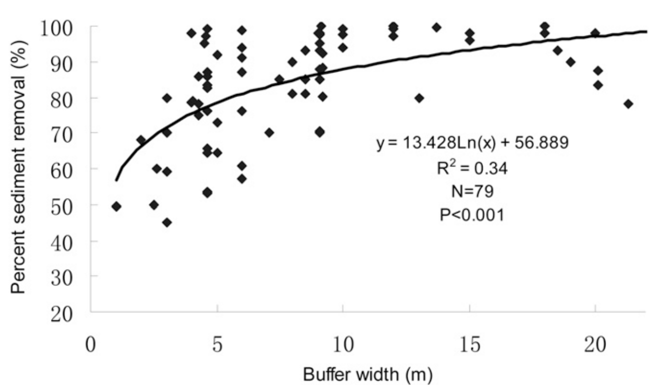

Fig. 2. Relationship between buffer width and percent sediment trapping efficacy.

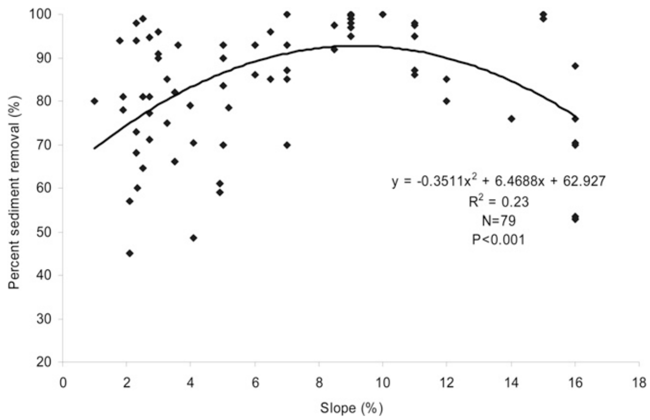

Fig. 3. Relationship between buffer slope and percent sediment trapping efficacy.

m^2 for seed or \$7.50 per m^2 for sod. This amounts to between \$3.20 and \$7.40 per m^2 of vegetated buffer. In the cases where the buffer filter strips have been seeded or sodded before using for BMP, the additional cost will be minimal. Maintenance of vegetated buffer strips consists mainly of vegetation management (mowing, irrigation if needed, weeding) and litter removal. Typical maintenance costs are about \$0.09/m^2/year (SWRPC, 1991). However, the costs are quite variable depending on the frequency of maintenance activities and the local labor rate.

It is shown in Fig. 2 that the sediment trapping efficacy is close to its maximum value when the buffer width is around 10 m. Most studies have been performed with buffer widths below 10 m (Table 1). Robinson et al. (1996) and Mickelson and Baker (1993) found that more than 70% of sediment load was removed by buffer strips less than 4.6 m wide, and buffer strips 9.1 m wide removed up to 85%. Dillaha et al. (1989) tested six filter strips with widths of 0, 4.6, and 9.1 m, and sediment trapping efficacy varied from 53 to 86% on the 4.6-m strips, and from 70 to 98% on the 9.1-m strips. Similar results were obtained by Magette et al. (1989), who tested filter strips vegetated with Kentucky-31 fescue established on a silty-loam soil. Removal efficacies of 66 and 82% were obtained for 4.6- and 9.2-m strips, respectively. This is in agreement with Coyne et al. (1995), who reported 99% sediment removal efficacy in two 9-m filter strips vegetated with tall fescue and Kentucky bluegrass at an even higher slope than the previously mentioned study by Magette et al. (1989). Abu-Zreig et al. (2004) conducted a total of 20 field experiments to examine the efficacy of vegetated filter strips for sediment removal from cropland runoff with varying buffer width. The results showed that buffer width was the predominant factor affecting sediment deposition up to 10 m. Similar results were obtained by Gharabaghi et al. (2002), who conducted an experimental study and found that the first 5 m of the filter strip was critical for sediment removal. However, sediment removal efficacy did not increase much beyond 10 m filter strip widths. Therefore, based on the data analysis, a 10-m buffer would be an appropriate choice for most sediment retention.

Table 2. Predicted sediment trapping efficacy for given buffer widths and slopes.

Scenarios	Buffer width	Buffer slope	Sediment trapping efficacy
	m		%
1	10	5	90.1
2	10	9	95.2
3	10	15	84
4	10	20	57.4
5	5	9	87.3
6	12	9	98.3
7	15	13	98.1

Buffer Slope and Sediment Trapping Efficacy

On buffers with steeper slopes runoff tends to flow through the buffer too fast, thus reducing sediment trapping efficacy to unacceptably low values. Likewise, buffers in flat areas are not suitable because the hydraulic gradient will be insufficient. In this review study, a second-order polynomial regression model ($R^2 = 0.23$, $P < 0.001$) was used to examine the relationship between buffer slope and sediment trapping efficacy (Fig. 3). With an increasing buffer slope, the sediment trapping efficacy increased until 9.2% slope and then decreased. Initially, sediment trapping efficacy increased with increasing buffer slope because a proper slope angle provides a runoff path to allow the vegetation to trap sediment. Eventually, as the slope increased, water flow velocity increased to a point where sediment deposition was limited. In this model, sediment trapping efficacy was maximized when the buffer slope was 9.2%.

Stepwise regression analysis of the factors buffer width, slope, area ratio, logarithmic function of width, slope, and area ratio, width^2, slope^2, and area_ratio^2 were used to select the main factors affecting sediment trapping efficacy. Buffer width, slope, and slope^2 were found to have the best correlation with sediment trapping efficacy. Equation [1] gives the relationship between buffer width, slope, slope^2, and sediment trapping efficacy, which was performed in SAS 9.1 with a satisfactory model result ($P < 0.0001$, $R^2 = 0.43$). It was found that to maximize sediment trapping efficacy ($Y_{sediment}$), the value of $5.67X_{slope}–0.314X_{slope}{}^2$ should be maximized when slope is 9%. This result is similar to the above slope result of 9.2%. Dillaha et al. (1988, 1989) installed vegetative filter strips with slopes of 11 and 16% and compared sediment removal with all other factors being constant. They derived an inverse relationship between slope and sediment entrapment. However, results of this study showed that a 9% buffer slope is an appropriate recommendation for sediment trapping when installing a new vegetated buffer.

$$Y_{\text{sediment}} = 53.77 + 1.58X_{\text{width}} + 5.67X_{\text{slope}} - 0.314X_{\text{slope}^2} \quad [1]$$

For various buffer widths and slopes, sediment trapping efficacy was predicted using Eq. [1] (Table 2). The results showed that when buffer width is 10 m and slope is 9%, the model predicts an efficacy of 95.17%, which correlates well with the data from the case studies. If buffer slope is greater than 9%, sediment trapping efficacy will decrease. Varying the width of the buffer zone produced a sediment trapping efficacy of 98.11%, even when the buffer slope was increased to 13%. Many review articles of buffer zone studies also conclude that buffers need to be wider when the slope is steep to allow more time for the velocity of surface runoff to decrease (Barling and Moore, 1994).

As with many other BMPs, criteria for the optimal grass buffer strip design are not readily available. Vegetated buffer efficacy is difficult to predict and this variability cannot be explained by buffer width or buffer slope alone. When implementing a vegetated buffer strip or other BMP, the designer faces a complex system where a large number of parameters and uncertainties need to be taken into account. Nonetheless, our meta-analysis results from current vegetated buffer literature can provide specific recommendations for future buffer construction and management.

Conclusions

This study reviewed over 80 scientific articles on vegetated buffers and sediment trapping efficacy. The efficacies of vegetated buffer filters in removing sediments are well documented. The large variations in buffer effects indicated that BMPs may not be uniformly successful across different regions and that the efficacy varied greatly with different site characteristics. The efficacy of a vegetated buffer is influenced by many factors such as buffer width, slope, area ratio, rainfall and vegetation. Based on available data, the relationship between sediment trapping and these factors was studied using stepwise regression analysis. The analysis showed that buffer slope and width are the two most important factors in determining sediment removal efficacy.

Review of the relationship between sediment trapping and buffer width showed that wider buffers provide a longer residence time for runoff water and thus, are more effective in reducing sediment. Model results suggested that buffer width alone can only explain about 29% of the variation. It was also shown that sediment trapping efficacy would not improve significantly when buffer width was increased beyond 10 m. Another important factor was buffer slope. A nonlinear relationship between sediment trapping and buffer slope was observed. As slope increased, the efficacy of the buffer increased; however, as the buffer became steeper, there was a point beyond which the efficacy of the sediment removal decreased. The trend suggested that there exists an optimal slope to achieve maximum efficacy. The low R^2 of 0.23 indicated that slope alone only explained approximately 23% of the variation. Other factors might also be important for the efficacies of vegetated buffers for sediment removal. By combining the two factors together we developed a relationship between sediment trapping and the two most important factors, buffer slope and width. From this regression analysis, an optimum slope of 9% was established. Therefore, buffers should be built with a slope that allows a consistent laminar flow across the buffer zone to improve the efficacies of sediment removal.

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