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A Review of effectiveness of vegetative buffers on sediment trapping in agricultural areas†

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ABSTRACT

In recent years, there has been growing recognition of the importance of riparian buffers between agricultural fields and waterbodies. Riparian buffers play an important role in mitigating the impacts of land use activities on water quality and aquatic ecosystems. However, evaluating the effectiveness of riparian buffer systems on a watershed scale is complex, and watershed models have limited capabilities for simulating riparian buffer processes. Thus, the overall objective of this paper is to develop an understanding of riparian buffer processes towards water quality modelling/monitoring and nonpoint source pollution assessment. The paper provides a thorough review of relevant literature on the performance of vegetative buffers on sediment reduction. It was found that although sediment trapping capacities are site- and vegetation-specific, and many factors influence the sediment trapping efficiency, the width of a buffer is important in filtering agricultural runoff and wider buffers tended to trap more sediment. Sediment trapping efficiency is also affected by slope, but the overall relationship is not consistent among studies. Overall, sediment trapping efficiency did not vary by vegetation type and grass buffers and forest buffers have roughly the same sediment trapping efficiency. This analysis can be used as the basis for planning future studies on watershed scale simulation of riparian buffer systems, design of effective riparian buffers for nonpoint source pollution control or water quality restoration and design of riparian buffer monitoring programs in watersheds. Published in 2009 by John Wiley & Sons, Ltd.

KEY WORDS grass buffer strips; grass hedges; riparian buffers; runoff; sediment trapping efficiency; nonpoint source pollution

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INTRODUCTION

In recent years, there has been growing recognition of the importance of vegetative buffers in controlling nonpoint source (NPS) pollution from agricultural fields. Vegetative buffers are strips of grass or stiff grass, trees or shrubs or combinations of grass and trees established at the edge of fields or along streams, ditches, wetlands, or other water bodies. They are designed to slow terrestrial inputs of water, trap sediment, filter nutrients, and provide habitat and corridors for fish and wildlife including important pollinator species. Riparian (streamside) buffers between agricultural fields and streams play an important role in controlling the impacts of land use activities on water quality and aquatic ecosystems, and they have been studied for the enhancement of water quality through control of NPS pollution and protection of the stream environment (Lowrance *et al.*, 1985, 1997, 2000; Hubbard and Lowrance, 1997; Lee *et al.*, 1999). Riparian vegetation has well-known beneficial effects on bank stability, biological diversity, and water temperature of streams (Lowrance *et al.*, 1997; Harmel *et al.*, 1999; Simon and Collsion, 2002; Sugden and Steiner, 2003).

Grass barriers or stiff grass hedges are usually hedges of stiff, perennial, and tall grass planted in 0·75–1·2-m wide strips (Kemper *et al.*, 1992). They are often established at short intervals (<15 m) in the field, paralleling rows of crops on the contour (Gilley *et al.*, 2000). Studies found that narrow stiff grass hedges were very efficient in dispersing concentrated flow and reducing gully erosion (Ritchie *et al.*, 1997; Ritchie, 2000). Edge of field grassed buffer strips are grass strips planted at the downslope of a field or plot. They differ in their design, vegetative species, and management (Blanco-Canqui *et al.*, 2004a,b). They have been demonstrated as effective sediment and nutrient filters (Dillaha *et al.*, 1989).

Numerous studies have been conducted to evaluate the effectiveness of vegetative buffers on NPS pollution and to determine the best design of buffer systems for maximum environmental benefits. Those studies are often conducted on plot scales and through field monitoring programmes. Long-term monitoring that reflects multi-year climatic variability and assures a range of events and conditions covered is needed for assessing the effectiveness of vegetative buffers (Shih *et al.*, 1994; Stone *et al.*, 2000; Borah *et al.*, 2003). However, long-term monitoring is very expensive and

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often limited by personnel and financial resources. In addition, although the effectiveness of vegetative buffers on a plot scale has been studied, their impact on a watershed scale is more complex and difficult to monitor. Thus, short-term field scale monitoring with complimentary simulation modelling can be used as an alternative for buffer system evaluation and planning.

Watershed simulation models have proven to be effective tools for evaluating watershed management efforts (Mitchell *et al*., 1993; Rosenthal *et al*., 1995; Arnold and Allen, 1996; Spruill *et al*., 2000; Arnold *et al*., 2001; Yuan *et al*., 2001; Yuan *et al*., 2006). However, watershed models such as the USDA Annualized Agricultural Nonpoint Source Polluting model (AnnAGNPS) (Bingner *et al*., 2003) have limited capabilities for simulating riparian buffer processes (Suttles *et al*., 2003; Liu *et al*., 2007). Although small field scale models such as the Riparian Ecosystem Management Model (REMM) (Lowrance *et al*., 2000) and Vegetative Filter Strip Modeling System (VFSMOD) (Muñoz-Carpena *et al*., 2007) were developed to simulate the impact of riparian buffer systems on water quality on a field scale, their impact on a watershed scale has not been evaluated. Thus, the overall objective of this paper is to develop an understanding of vegetative buffer processes and their effectiveness towards water quality modelling/monitoring and NPS pollution assessment on a watershed scale. The first step is to do a thorough review of relevant literature on field evaluations of the performance of vegetative buffers on sediment reduction. This analysis can be used as the basis for planning future studies on watershed scale simulation of vegetative buffer systems, design of effective vegetative buffers for NPS pollution control or water quality restoration, and design of vegetative buffer monitoring programmes in watersheds.

Dosskey (2001) provided an overall review of reduction on NPS pollutant through installation of buffers on crop land. He reviewed effectiveness of buffer on sediment, nutrients, and pesticides reduction; and water pollution abatement of surface water and groundwater. Therefore, information on effectiveness of buffer on sediment trapping is very limited in his review. The author qualitatively discussed the factors affecting the effectiveness of buffer, but no attempt was made to quantify those factors. This paper provides an overview of current level of research on riparian buffers' effectiveness in removing sediment from agricultural runoff and should help to identify trends and develop theoretical relationships between buffer characteristics and sediment removal capacity. Earlier studies on sediment removal capacity were reviewed and reported in this paper. Buffer characteristics of interest include vegetation type and width. Soil type and slope, sediment particle size, and rainfall/runoff also were considered as factors affecting the effectiveness of buffer in removing sediment. In the scientific literature, riparian buffer is often used interchangeably with vegetative filter or vegetative buffer, and the original terminology was preserved when referring to published studies in this paper.

METHOD AND PROCEDURES

The focus of this review is on the effectiveness of buffer systems on water quality, particularly on sediment removal. Results from peer-reviewed research papers that contain original data quantifying the effects of buffer on sediment removal were summarized based on buffer width, types of vegetation, amount of material entering the buffer, sediment particle size determined by soil type, slope, rainfall, and runoff characteristics.

Sediment trapping efficiency (Dabney *et al*., 1995) is one parameter that can be used to calculate the effectiveness of a riparian buffer to filter out sediment and is:

$$T_{\mathrm{E}} = (M_{\mathrm{i}} - M_{\mathrm{o}})/M_{\mathrm{i}} = 1 - \frac{M_{\mathrm{o}}}{M_{\mathrm{i}}} = 1 - \mathrm{SDR} \qquad (1)$$

where T_{E}, trapping efficiency; SDR, sediment delivery ratio; M_{i}, total mass flowing onto the buffer zone (tons/ha.); M_{o}, total mass flowing out of the buffer zone (tons/ha.).

Sediment trapping efficiency was plotted against buffer width, and linear and nonlinear regression models were fitted to the data to reveal patterns of sediment removal based on width. All buffer studies where sediment trapping efficiencies could be calculated were included in this analysis. Sediment trapping efficiency was also evaluated against buffer width by vegetation cover type.

Vegetative buffer systems are strips of grass or stiff grass, trees or shrubs, or combinations of grass and trees established at the edge of fields or along streams. Thus, results are presented in a hierarchy from simple to more complex buffering systems: (1) studies on grass barriers or stiff grass hedges and filter strips (FS) are presented first; (2) studies on riparian buffer systems which consist of a grass FS and trees or shrubs are followed.

RESULTS

Synthesis of research on grass barriers or stiff grass hedges and FS

Grass barriers are usually hedges of stiff, tall, perennial dense vegetation which are also called stiff grass hedges (Dabney *et al*., 1993) and are planted in 0·75–1·2 m wide strips (Kemper *et al*., 1992), whereas FS are wider strips of vegetation established between agricultural lands and streams or at field edge in 5–15 m wide strips (Dillaha *et al*., 1989). Stiff grass hedges differ from buffer strips in that they are narrow and require less land area. Stiff grasses are planted perpendicular to the slope and managed to encourage formation of berms by sediment deposited from upslope or within the vegetated area. Because stiff grasses have more robust stems, they are more resistant to inundation by concentrated flow than standard buffer strips. Thus, they offer important advantages in areas of concentrated flow, although they may be less effective than standard buffer strips or FS where flow rates are relatively small (Dabney *et al.*, 1993; Ritchie *et al.*, 1997; Ritchie, 2000; Blanco-Canqui *et al.*, 2004b, 2006). Grass barriers are also very effective in controlling soil erosion from forest road sideslopes (Grace, 2002).

Grass barriers or stiff grass hedges. Ritchie *et al.* (1997) and Ritchie (2000) compared the land survey measurements before, 4 and 7 years after the grass hedge established. They found that 8–15 cm sediment was deposited above grass hedges in the first 4 years. Deposition patterns were related to the original topography with low areas having the greatest deposition. About 1–2 cm per year of recent sediment was deposited upslope of the grass hedge in the last 3 years.

Gilley *et al.* (2000) evaluated the performance of narrow switchgrass hedges on runoff and soil erosion under no-till and tilled conditions at the USDA-ARS-National Soil Tilth Laboratory Deep Loess Research Station. The Deep Loess Research Station is located approximately 19 km east of Council Bluffs, Iowa and is typical of Monona (fine silty, mixed, superactive, mesic Typic Hapludolls) soil type. The study site had been in continuous corn for 33 years, and the grass hedges had been established for 6 years at the time of testing. The area above the grass hedges had slope gradients ranging from 8% to 16%. The experimental plots were set up as 3·7 m wide by 10·7 m long, and treatments were: (1) no-till or tilled soil conditions; (2) the presence or absence of a 0·72 m (2·4 ft) grass hedge; and (3) corn residues or without corn residues. Grass hedges were mowed to a height of approximately 460 mm (18 in.) before the rainfall application. Rainfall was first applied at an intensity of 64 mm h^{-1} for an hour to wet the soil, then after 24 h another hour of rainfall was applied at the same intensity, runoff and erosion measurements with and without grass hedges were collected from different plots. In summary, grass hedges were very effective in reducing soil loss, and the 0·72 m switchgrass hedges reduced soil loss by 63%.

McGregor *et al.* (1999) evaluated the performance of grass hedges and the effectiveness of no-till cropping systems in reducing soil loss on standard erosion plots at Holly Springs, Mississippi. Erosion plots were 4 m wide and 22·1 m long on 5% slopes. Soils on the plots were predominantly Providence silt loam. During 1992–1994 when data were collected, the 3-year average rainfall was 1386 mm, similar to the 30-year normal rainfall of 1372 mm for North Central Mississippi. It was concluded that grass hedges reduced average annual runoff on conventional-till cotton plots by 5% and on no-till plots by 7%; and reduced average annual soil loss on conventional-till cotton plots by 75% and on no-till plots by 57%.

Raffaelle *et al.* (1997) evaluated the relative effectiveness of grass strips when used with different management practices by comparing soil loss from bare fallow, conventional-till, and no-till plots with narrow (0·6 m wide) grass strips planted at the bottom of plots or without. The study was performed at Holly Springs, Mississippi. Their experimental plots were constructed as 3·7 m wide and 10·1 m long with slightly irregularly shaped slopes with a steepness of approximately 10%. Soils on the plots were classified as Lexington silt loam (Typic Paleudalfs). Experimental plots had been in volunteer grass, predominantly Bermuda grass since 1973, except in 1985 when no-till soya beans were grown on them and in 1986 when no-till grain sorghum was grown. From mid-June through July of 1993, 1994, and 1995, simulated rainfall (64 mm h^{-1}) was applied for 2 h to experimental plots. The simulated rainfall was initially applied for 1 h on the dry soil 'dry run', followed 4 h later by a 30 min 'wet run' and 30 min waiting period by a final 30 min 'very wet run'. Data collected from experiments were summarized in Appendix A. It was concluded that the grass hedge reduced average soil loss on conventional-till by 63%, on no-till plots by 54%, and on bare fallow by 84%.

Meyer *et al.* (1995) constructed a 0·305 m wide, 0·61 m high, and 10 m long transparent wall flume of aluminium and clear plastic sheets to evaluate the effectiveness of stiff grass hedges for retarding runoff and trapping transported sediment in concentrated runoff in major upland channels. The flume was set at a 5% slope. They tested several types and arrangements of grasses using different flow rates, types of sediment and sediment concentrations. The grass hedges placed into the flume were from 150 to 760 mm wide in the direction of flow. Inflows were from 0·66 and up to 2·6 m^3 min^{-1} per meter of flow width. Sediments used included the subsoil of a Smithdale sandy loam (fine-loamy, siliceous, thermic Typic Hapludults), Ap horizon from a Grenada silt loam soil (fine silty, mixed, thermic Glossic Fragiudalfs), and two Dubbs sandy loam soils (fine silty, mixed, thermic Typic Hapludults). They found that among the various hedges they tested, three types of hedges were most effective: vetiver, narrow switchgrass-fescue combination, and wide switchgrass (tables 2 and 3 in Meyer *et al.*, 1995). As Meyer *et al.* (1995) and Dabney *et al.* (1995) observed, sediment trapping by a narrow stiff grass hedge is primarily from settling in the backwater upslope of the hedge. Sediment characteristics greatly affected sediment trapping, flow rate had some effect, but sediment concentration had little effect (figure 5 in Meyer *et al.* (1995)). As shown in tables 2 and 3 (Meyer *et al.*, 1995), among the different switchgrass arrangements, the wide 760 mm hedge of Kanlow was considerably more effective than the 140 mm Kanlow hedge, but the combination of fescue before wild switchgrass (350 mm) was as effective as the wider Kanlow hedge (760 mm). It was found that the major effect of the type of grass was on flow ponding which was directly linked with the stem characteristics as they affected ponded depth.

As the depth of ponding increased, the trapping efficiency increased and the longer and deeper pool also increased the volume of sediment that could be stored before the delta of deposited sediment reached the hedge (Dabney *et al*., 1995). Also, as shown in tables 2 and 3 in Meyer *et al*. (1995), trapping efficiency of these hedges decreased less as flow increased than did the effectiveness of the other hedges; and the fraction trapped decreased only a few percent as flow doubled from 1·3 to 2·6 m^3 min^{-1} m. A higher trapping efficiency of switchgrass and vetiver for the Dubbs II sediment than for the finer Dubbs I and Grenada sediments was observed. It was determined that nearly all of the sand-size sediment was trapped by the hedges, and the outflow from the hedges is dominated by silt and clay-size sediment. The trapped portion of sediment decreased as flow rate increased.

The following flow and trapping effectiveness relationship was suggested by Meyer *et al*. (1995):

$$Y = 1 - aQ^b \quad (2)$$

where Y, fraction trapped; Q, flow rate (m^3 min^{-1} m); a, coefficient; and b, exponent; a and b are functions of the sediment-size and particle distribution. The following coefficients and exponents were obtained from Dubbs II sediment during Meyer *et al*. (1995) experiments.

Sediment size	*a*	*b*
>125 μm	0·025	2
32–125 μm	0·39	0·5
<32 μm	0·78	0·08

Based on their relationship and a and b obtained from Meyer *et al*. (1995), sediment that can be trapped by various hedges for a wide range of sediment and flow conditions can be estimated. Meyer *et al*. (1995) suggested that in the absence of sediment-size distributions, particle size distributions can be estimated from analysis of bulk soil samples for the sediment resulting from inter-rill erosion. Foster *et al*. (1985) describe a method for evaluating sediment-size distributions of five broad size density classes using a soil's primary particle size distribution.

For channel slopes different from 5% studies in Meyer *et al*. (1995), the portion trapped would likely increase for flatter grades and decrease for steeper grades because of their effect on length of the ponded area. Meyer *et al*. (1995) study again showed that although type of grass hedge and flow rate are important, sediment-size distribution usually will primarily govern trapping efficiency as described by the equation.

In addition to use at the edge of fields, grass barriers are also established at short intervals (<15 m) in the field, paralleling rows of crops on the contour (Kim *et al*., 2008). This cropping system is also called alley cropping (Kim *et al*., 2008). Kim *et al*. (2008) studied the effectiveness of hedgerows of mimosa (Albiziajulibrissin), blackberry (Rubus ursinus), and switchgrass (Panicum virgatum) on alley cropping treatment for sediment reduction in Cullman, AL. From August 2002 to July 2004, surface runoff and sediment data were collected from plots dominantly in Hartsells sandy loam soil with 6·5% slope. They found that blackberry, switchgrass, and hedgerows of mimosa reduced runoff by 45%, 62%, and 74%, respectively. Switchgrass and hedgerows of mimosa reduced sediment yield by 76% and 84%, respectively. The effectiveness of vegetative barriers in reducing surface runoff, sediment concentration, and yield progressively improved over time. Switchgrass hedges were more effective than blackberry and mimosa hedgerows in reducing runoff and sediments due to their rapid establishment.

Grass FS. Dillaha *et al*. (1989) evaluated the effectiveness of orchardgrass FS in removing sediment and nutrients from cropland runoff on eroded Groseclose silt loam soil at the Prices Fork Research Farm near Blacksburg, Virginia. In their study, they established nine experimental field plots with a 5·5 by 18·3 m bare ground source area and a 0, 4·6, or 9·1 m orchardgrass FS located at the lower end of each plot. Simulated rainfall was applied to each set of plots for 1 h, followed 24 h later by two 30 min runs, which were 30 min apart. Runoff and runoff samples were collected at the end of each plot. Results are reported in Appendix A. The plot with wider grass strip (9·1 m) consistently reduced more sediment than the narrower grass strip (4·6 m).

Magette *et al*. (1989) evaluated the effectiveness of fescue FS in removing sediment and nutrients from cropland runoff on Woodstown sandy loam soils. In their study, they established nine experimental field plots with a 5·5 by 22 m bare ground source area and a 0, 4·6, or 9·2 m fescue FS located at the lower end of each plot. Simulated rainfall was applied to each set of plots for one hour at an intensity of 48·3 mm h^{-1}, followed 24 h later by two 30 min runs, which were 30 min apart. Runoff and runoff samples were collected at the end of each plot. Results are reported in Appendix A. The plot with wider grass strip (9·2 m) reduced more sediment than the narrower grass strip (4·6 m).

Robinson *et al*. (1996) evaluated the effectiveness of bromegrass FS in removing sediment from cropland runoff on Fayette silt loams in northern Iowa. In their study, they established study areas on 7% and 12% grades. Soil loss from an 18·3 m continuous fallow strip was used as the source area to the FS. Runoff collectors were placed at various intervals within the bromegrass FS and data was recorded from 13 rainfall events. They found that the initial 3·0 m of the FS removed more than 70% of the sediment from runoff, while 9·1 m of the FS removed 85%. Little change in sediment concentration was observed beyond a width of 9·1 m.

Rankins *et al.* (2001) conducted field studies in 1996, 1997, and 1998 to evaluate the effectiveness of several grass FS for reducing sediment and herbicide losses in runoff at the Mississippi Agricultural and Forestry Experiment Station Black Belt Branch near Brooksville, MS. Soils in the experimental plots are Brooksville silty clay (fine montmorillonitic, thermic Aquic Chromudert; 3·0% slope, 3·2% organic matter). Big bluestem, eastern gamagrass, switchgrass, and tall fescue were evaluated in their study. Within the 127-day sampling period, each perennial grass FS investigated reduced total sediment loss in surface runoff by at least 66%.

McKergow *et al.* (2004) evaluated the effectiveness of vetiver buffers in removing sediment on planar and convergent slopes under field condition in Far North Queensland. Their experimental condition is extreme for testing the effectiveness of buffer because the land is steep, intensely cropped and receives high intensity rainfall. Even under those extreme nature conditions, they found that grass buffer strips were able to trap 65% suspended sediment within the first 15 m.

The combination of grass barriers with FS. Blanco-Canqui *et al.* (2004a,b, 2006) evaluated the performance of grass barriers, FS and the combination of two under inter-rill and concentrated flow at the University of Missouri's Bradford Center. Bradford Center is located 17 km east of Columbia, MO and is typical of moderated eroded Mexico soil. In their first study, they established twelve 1·5 by 16 m plots with four treatments replicated three times in a randomized complete block design to evaluate the performance of grass barriers, FS, and the combination of the two under inter-rill flow conditions. Plots were planned with 1·5 by 8 m pollutant source area under continuous cultivated fallow (CCF) above an 8 m test area. Four treatments for testing area are CCF which is without switchgrass barrier or FS, fescue filter strip (Fescue-FS), switchgrass barrier combined with fescue filter strip (B-Fescue-FS) and switchgrass barrier combined with native plant species filter strip (B-native-FS). As shown in figure 1 in Blanco-Canqui *et al.* (2004a), a 0·7 m switchgrass barrier was established at the downslope edge of the pollutant source area just above the FS. An hour rainfall at intensity of 66 mm h^{-1} was applied to each plot to wet the soil, and 24 h later a subsequent rainfall at the same intensity and duration was applied to produce runoff. This was designed to produce large rainfall events when most soil erosion is likely to occur. Runoff and runoff samples were collected at 1 m above the downslope edge of the source area and in the testing area at 0·7, 4, and 8 m below the source area. Runoff samples were analysed for sediment concentration. Collected data are summarized in Appendix A. Switchgrass barriers were more effective than an equal width (0·7 m) of fescue FS for reducing runoff and sediment.

In their second study, Blanco-Canqui *et al.* (2004b) evaluated the performance of grass barriers, FS, and

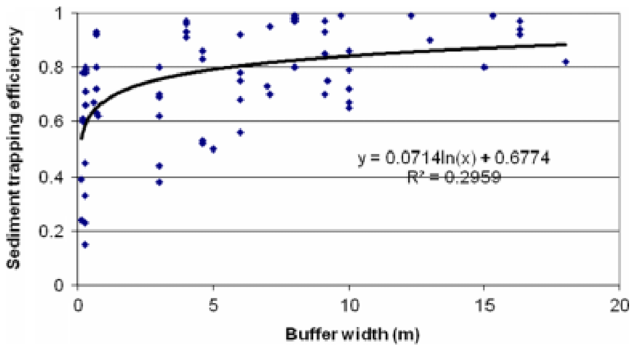

Figure 1. Buffer width and sediment trapping efficiency.

the combination of the two under concentrated flow conditions. They established eighteen 1·5 by 16 m plots with six treatments replicated three times in a randomized complete block design. The six treatments were: (1) a fescue FS; (2) a switchgrass barrier above a native species FS; (3) concentrated flow above a fescue FS with no barrier; (4) concentrated flow above a barrier plus fescue FS (B-FS); (5) a switchgrass barrier above a fescue FS; and (6) a check managed in CCF without switchgrass barrier or FS. Each plot was planned with 1·5 by 8 m pollutant source area under CCF above an 8 m test area. Switchgrass barriers were established at the downslope edge of the pollutant source area just above the FS as the first study. A V-shaped channel, 200 mm wide by 100 mm deep, was constructed in the centre of the sediment source area to simulate concentrated flow conditions. Simulated rainfall was applied the same way as the first study. Runoff and runoff samples were collected at 1 m above the downslope edge of the pollutant source area and in the testing area at 0·7, 4, and 8 m below the pollutant source area. Runoff samples were analysed and results are also reported in Appendix A. They found that differences between B-FS and FS were significant for trapping sediment. The B-FS trapped significantly more sediment than FS. Bharati *et al.* (2002) found that cumulative infiltration under switchgrass was significantly higher than that in row crop and pasture. Sediment was reduced with distance for both treatments, but differences between B-FS and FS at the 8 m position were not significant. Most sediment (>60%) were trapped in the upper 0·7 m strip of B-FS and FS below the source area. Additionally, the authors found that the effectiveness of the FS treatment for reducing sediment loss decreased with increased inflow rates, but this is not the case for the B-FS treatment.

In the Blanco-Canqui *et al.* (2006) third study, they evaluated the performance of switchgrass barriers (0·7 m) planted above fescue FS under inter-rill and concentrated flow conditions and fescue FS alone under inter-rill and concentrated flow conditions separately. As shown in Appendix A, they found that FS under inter-rill flow condition reduced 80% and those under concentrated flow conditions reduced 72% of sediment at 0·7 m. As runoff increased, the efficiency under concentrated flow decreased to 60%. The effectiveness of both treatment increase with increasing width, FS under concentrated flow reduced less sediment than inter-rill flow at 8 m. In contrast, barriers above FS under inter-rill and concentrated flow were equally effective at 8 m. Thus, barriers combined with FS can be an effective alternative to FS alone for sites where concentrated flows may occur.

Synthesis of research on riparian buffer systems

Riparian buffer systems can consist of any combination of vegetative conditions that includes a grass FS immediately downslope from an agricultural field, a wide, rapidly grown management forest zone which can be harvested and an undisturbed forest located adjacent to the stream drainage system which includes aquatic plants in shallow water and moisture-loving plants along the shore (Schultz *et al*., 1995). The buffers can be comprised of existing plants on the site and/or new plantings. Many studies have shown that riparian buffer systems are very efficient in reducing sediment and nutrient loadings to the stream system with the primary runoff and sediment reductions contained within the grass filter portion of the riparian systems.

A three-zone riparian buffer system was established in 1992 at the Gibbs Farm in the Georgia Coastal Plain near Tifton, GA (Sheridan *et al*., 1999). Zone 1 is adjacent to the stream, and consists of a 10 m wide undisturbed native hardwood forest area for protecting the stream bank and aquatic environment. Zone 3 is farthest away from the stream and adjacent to the field. Zone 3 is designed as an 8 m wide herbaceous grass FS for dispersal of incoming upland surface runoff, sediment and nutrient deposition. Zone 2, between zone 1 and zone 3, is a 45–55 m managed coniferous forest. Three management practices, mature forest (MF), clear cutting (CC), and selective thinning (ST) were maintained for the riparian buffer system (Sheridan *et al*., 1999). Sheridan *et al*. (1999) studied the impact of forest management practices implemented within the riparian buffer system on runoff and sediment reduction. They found that roughly 80% of the sediment was removed after passing through the 8 m wide herbaceous grass FS (zone 3). Therefore, the fast grown forest zone (zone 2) can be managed for economic return. The riparian buffer system practices of CC, ST, or MF implemented in the riparian buffer system did not cause significant differences in runoff and sediment within the zone because the primary runoff and sediment reductions are within the grass filter portion of the riparian buffer system.

A multi-species riparian buffer strip (MRB) system was established along the Bear Creek, Story County of Central Iowa in 1990 (Schultz *et al*., 1995). Bear Creek is typical of many streams in Central Iowa where the primary land use along the stream's length is row crop (corn and soya beans) production or intensive riparian zone livestock grazing. The buffer system is about 20 m wide consisting of four or five rows of fast growing trees next to the stream, then two shrub rows, and finally a 7 m wide strip of switchgrass below agricultural fields. Several studies of evaluating the performance of the buffers were conducted since its establishment. Lee *et al*. (1999) compared the effectiveness of 6 and 3 m wide FS of switchgrass (Panicum virgatum) and cool-season FS consisting of bromegrass (Bromus inermis), timothy (Phleum pratense), and fescue (Festuca spp.) in reducing sediment in surface runoff from adjacent crop fields using simulated rainfall and runoff. The 6 and 3 m wide strips represented 20 : 1 and 40 : 1 area ratios, respectively. Twelve plots, six each, in the switchgrass and cool-season grass strips, were laid out on Coland soil, a fine-loamy, mixed, mesic cumulic haplaquolls, with an average slope of 3%. Simulated rainfall of 5·1 cm h^{-1} intensity was applied on experimental plots; then runoff was collected from each plot and analysed for sediment. The 6 m wide FS removed 77% while the 3 m removed 66% of the incoming sediment from surface runoff. The differences between 6 and 3 m FS were significant for sediment removal. Lee *et al*. (2000) evaluated the ability of the multi-species riparian buffer in removing sediment, nitrogen, and phosphorus from cropland runoff under simulated rainfall. During this study, simulated rainfall was applied to 4·1 by 22·1 m bare cropland source area paired with either no buffer, a 7·1 m wide switchgrass buffer, or a 16·3 m wide switchgrass/woody plant buffer (7·1 m switchgrass/9·2 m woody plant). Treatments were replicated 3 times, thus total 12 plots were set up. Two-hour rainfall at 25 mm h^{-1} and 1 h rainfall at 69 mm h^{-1} were applied to experiments plots. In a companion paper, with the study conducted at the same location, Lee *et al*. (2003) evaluated the effectiveness of the multi-species riparian buffer in removing sediment, nitrogen and phosphorus from cropland runoff under natural rainfall events. Results are summarized in Appendix A. During those two studies, it was determined that the switchgrass was effective in trapping coarse sediment and sediment-bound nutrients. The additional buffer width with the deep-rooted woody plant zone was effective in trapping the clay and soluble nutrients. Overall, the combinations of the dense, stiff, native grass, and woody vegetation improved the removal effectiveness for the NPS pollutants from agricultural areas. In addition, there was a significant negative correlation between the trapping effectiveness of the buffer and the intensity and total rainfall of individual storms.

A multi-species RB system was planted in 2000 below a steep-sloping field in row-crop production under no-tillage management in Iowa's Loess Hills (Tomer *et al*., 2003). The multi-species buffer is composed of three zones of vegetation, including 5 m switchgrass at the crop-field edge, a 5 m brome and alfalfa mix in the middle, and four rows of poplar with one row of walnut trees planted in the centre. Tomer *et al*. (2007) studied the accumulations of sediment and phosphorus in this multi-species riparian buffer and characterized spatial-temporal patterns of phosphorus in riparian soil water and groundwater. They found that sediment accretion was associated with concentrated flow pathways and lateral flow along the buffer-crop margin through topographic surveys conducted in 2002 and 2005. Mapped differences in elevation showed that about 32% of the buffer's outer switchgrass (*Panicum virgatum* L.) zone had sediment accumulations exceeding 4 cm (1·6 in.), which totalled 14·5 Mg ha^{-1} (over 3 years) contributing area, or 4·8 Mg ha^{-1} $year^{-1}$ (2·1 t ac^{-1} $year^{-1}$).

Mankin *et al.* (2007) evaluated the ability of grass-shrub riparian buffer system in removing total suspended solids (TSS), phosphorus (P), and nitrogen (N) from simulated runoff. Their study site was located in North-eastern Kansas, along a tributary of the West Branch Mill. To assess the influence of buffer width and vegetation type on the overall reductions of pollutants, three treatments: (1) all natural selection grasses (NS); (2) two-zone buffer with native grasses and plum shrub (NG/P); and (3) two-zone buffer with natural selection grasses and plum shrub (NS/P) were studied. Both the NS and NG areas were in good condition with greater than 98% ground cover. The planted American plums had reached crown closure and averaged 2·5 m in crown height and canopy width. Each treatment was repeated 3 times, so totally 9 plots were set up. The buffer width ranges from 8·3 to 16·1 m. Simulated runoff with 4433 mg l^{-1} TSS from on-site soil was applied to each study plot. Flow-weighted samples were collected after runoff passing through the buffer. Appendix A shows the results from this study. The authors concluded that the buffers were very efficient in removal of sediment with removal efficiencies strongly linked to infiltration. Mass and concentration reductions averaged 99·7% and 97·9% for TSS. Infiltration alone could account for >75% of TSS removal. Vegetation type induced significant differences in removal of TSS. These results demonstrate that adequately designed and implemented grass-shrub buffers with widths of only 8 m provide for water quality improvement, particularly if adequate infiltration is achieved.

Daniels and Gilliam (1996) evaluated the ability of grass or grass-tree riparian buffer in removing sediment and chemical loading from agricultural runoff at two locations representing different major soil-geomorphic systems in the North Carolina Piedmont. Runoff was collected from cultivated fields at four sites from the edge of the field and through the filter. Results were reported in Appendix A. They found that both grass and grass-riparian FS reduced the sediment load of field runoff. The effectiveness varied with the erosiveness of the watershed and storm intensity, but across a wide range of rainfall, FS reduced sediment load 60–90%.

Borin *et al.* (2005) evaluated the ability of the 6 m buffer strip consisting of two rows of trees with grass planted in the middle in removing pollutants from cultivated field in Northeast Italy. During the 3-year study, the sediment was reduced more than 92% with the buffer compared with the study site without the buffer.

Schoonover *et al.* (2006) compared the performance of giant cane and mixed deciduous forest buffer on sediment reduction from a non tile-drained agricultural watershed in Southern Illinois. The contributing area of the field draining into the buffers was 0·26 ha with an average slope of 1%. The soils were classified as Haymond silt loam. Data collected from both buffers at the edge of field and at 3·3, 6·6, and 10·0 m within the buffers over a 1-year period were reported in Appendix A. On an annual basis, significant sediment reduction occurred by 3·3 and 6·6 m in the cane and forest buffers, respectively. The giant buffer reduced incoming sediment mass by 94% within the first 3·3 m, while the forest buffer reduced sediment by 86% over 6·6 m. Within 10 m of the buffer, the cane reduced sediment mass by 100%, while the forest buffer reduced sediment by 76%.

White *et al.* (2007) studied the capacity of forested FS to retain sediment and the relationship between sediment retention and FS characteristics of forest FS in the Piedmont of Georgia. They found that runoff concentration of particles >20 μm in diameter were largely retained in the first 2 m of the FS by settling. Retention of the 2–20 μm size fraction was correlated to flow distance within the FS, and a 16 m wide FS removed most 2–20 μm size sediments from runoff water. The runoff concentration of particles <2 μm in diameter was not affected by the FS, but some retention occurred through infiltration. Observed reduction in total sediment within the 10 m FS ranged from 53% to 96% from this study.

DISCUSSION

Overall buffer effectiveness

Vegetative buffer strips significantly reduce sediment loading in surface runoff from agricultural fields based on above reviews. Buffers remove sediment from the overland flow by decreasing its velocity and allowing particles to settle. Increased water infiltration into the soil profile within buffer zones also aids in sediment interception by decreasing the amount of runoff. The effectiveness of buffers in removing sediment varied widely among the studies (Appendix A). Sediment trapping efficiency, which was defined as the capacity of a buffer to retain a fraction of sediment from incoming runoff, is typically used to define the buffer effectiveness. Overall results showed that the trapping efficiency in buffers depends primarily on buffer width, vegetation type, density and spacing, sediment particle size, slope gradient and length, and flow convergence. Other factors also affect sediment trapping efficiency include soil properties, initial soil water content, and rainfall characteristics (total amount and intensity).

Results indicated that under conditions of relatively shallow flow not concentrated in channels, gently sloping, densely vegetated 3 m buffers are likely to limit transport of sediment from uplands to streams (Robinson *et al.*, 1996; Lee *et al.*, 1999; Rankins *et al.*, 2001; Blanco-Canqui *et al.*, 2004a,b), whereas moderately steep, less densely vegetated buffers of 3 m may be vulnerable to much higher rates of sediment delivery (Daniels and Gilliam, 1996). The first 3–6 m of a buffer plays a dominant role in sediment removal (Daniels and Gilliam, 1996; Robinson *et al.*, 1996). For example, Robinson *et al.* (1996) found that sediment was reduced by 70% and 80% from the 7% and 12% slope plots, respectively, within the first 3 m of the buffer. Dillaha *et al.* (1989) and Magette *et al.* (1989) reported sediment trapping efficiencies of 70–80% for 4·6 m and 84–91% for 9·1 m wide grass FS. Generally, buffers 4–6 m can reduce sediment loading by more than 50% (Magette *et al.*, 1989; Daniels and Gilliam, 1996; Lee *et al.*, 1999; Blanco-Canqui *et al.*, 2004a,b; Borin *et al.*, 2005). However, the efficiency is likely reduced on slopes above 5 degrees due to the vegetation becoming flattened by surface runoff during high rainfall. A narrower buffer was found to be effective for less erodible soils.

Buffers greater than 6 m are effective and reliable in removing sediment from any situation; for example, Hook *et al.* (2003) reported that more than 97% of sediment was trapped in the rangeland riparian buffer area with a 6 m buffer in any of the experimental conditions they studied. Sheridan *et al.* (1999) reported sediment trapping efficiencies of 77–90% across three different management schemes (clear cut, thinned, and untouched) when studying the impact of forest management practices within the riparian zone. Cooper *et al.* (1992) estimated that 90% of the sediment leaving fields was retained in the wooded riparian zone.

Effect of buffer width on sediment trapping efficiency

Wider buffers tended to trap more sediment, but other factors also influence efficacy. Overall, the sediment trapping efficiency to buffer width relationship can be best fitted with logarithm models (Figure 1). According to this relationship, a 5 m buffer can trap about 80% of incoming sediment. It is additionally observed that effectiveness differed among buffer width categories (Figure 2). Buffers of 3–6 m wide have greater sediment trapping efficiency than buffers of 0–3-m wide, and buffers of greater than 6 m wide have greater sediment trapping efficiency than buffers of 3–6 m wide. Thus, wider buffers are likely to be more efficient in trapping sediment than narrower buffers.

Effectiveness of slope on sediment trapping efficiency

Sediment trapping efficiency is also affected by slope, but the overall relationship is weak (Figure 3). Studies done by Blanco-Canqui *et al.* (2004a, 2004b), and

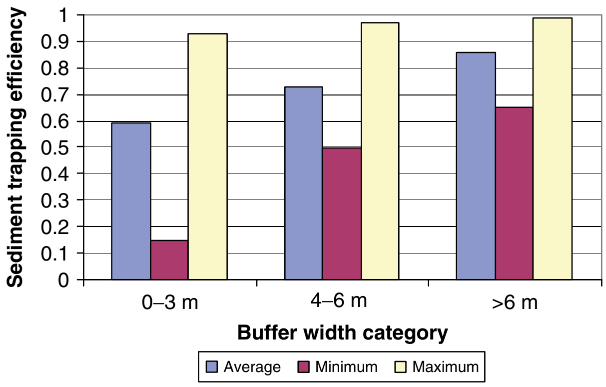

Figure 2. Average, minimum, and maximum sediment trapping efficiency for different buffer width category.

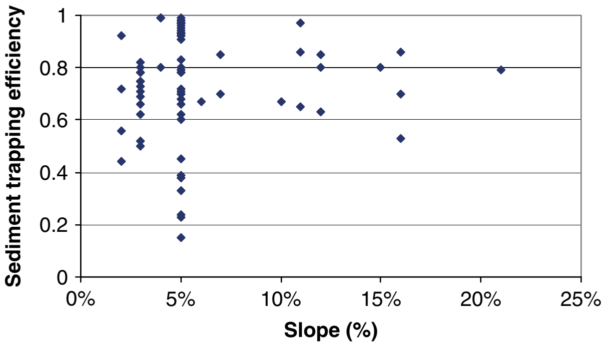

Figure 3. Slope and sediment trapping efficiency.

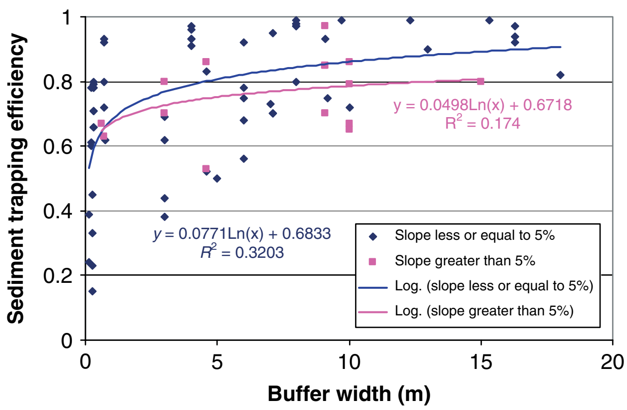

Figure 4. Slope and sediment trapping efficiency.

Gilley *et al.* (2000) showed that for buffers about the same width (0·7 and 0·72 m), sediment trapping efficiency was lower with a greater slope (5% vs 8–16%, Appendix A). However, Dillaha *et al.* (1989), Robinson *et al.* (1996), and White *et al.* (2007) all observed that sediment trapping efficiency is not necessarily lower with greater slopes. In the study done by Dillaha *et al.* (1989), they actually found that the sediment trapping efficiency increased as the slope increased from 5% to 11% given the same buffer width. However, as the slope increased to 16%, the sediment trapping efficiency decreased (Appendix A). The sediment trapping efficiency was the lowest with 16% slope (Dillaha *et al.*, 1989; Appendix A). Additional analysis of buffer efficiency with buffer

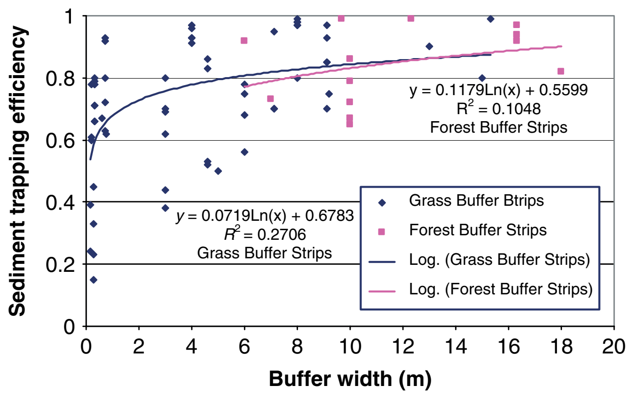

Figure 5. Vegetation type and sediment trapping efficiency.

width for different slope categories showed that buffers appeared to be less effective when slopes are greater than 5% than with slopes that are less or equal to 5% (Figure 4).

Effectiveness of vegetation type on sediment trapping efficiency

Overall, sediment trapping efficiency did not vary by vegetation type. Both forested and grassy vegetation can filter sediment from upland runoff, and grass buffers and forest buffers have similar sediment trapping efficiencies (Figure 5). There is insufficient data to determine the relative effectiveness of forested versus grassy vegetation due to a lack of detailed studies on this topic. However, forest buffer strips were usually wider than grass buffer strips based on references found in this study (Figure 5). For grass buffer strips, switchgrass buffer strips seem more efficient in trapping sediment than an equal width of fescue FS (Rankins *et al.*, 2001; Blanco-Canqui *et al.*, 2004a) and cool-season grasses (Lee *et al.*, 1999). However, Rankins *et al.* (2001) found that big bluestem and eastern gamagrass were more efficient in trapping sediment than switchgrass.

Future research needs

Information is lacking on the overall impact of vegetative buffers on sediment trapping at a watershed scale. For a typical watershed, because of the heterogeneity of the watershed (many land uses, many types of soils and different topography), what would be the best locations to install vegetative buffers to reduce sediment delivery to the watershed outlet such as a reservoir. What would be the overall water quality impact downstream and downstream lakes for buffers installed upstream of the watershed? Watershed scale models may provide an alternative way to help understand this missing information.

SUMMARY AND CONCLUSIONS

Although sediment trapping capacities are site- and vegetation-specific, and many factors influence the sediment trapping efficiency, the width of a buffer is important in filtering agricultural runoff. Grass buffers as narrow as 3 m can remove significant amounts of sediments from agricultural runoff with a maximum benefit achieved with widths of 6 m or more. The Natural Resources Conservation Service (NRCS) has recommended a minimum grass buffer width of 8–10 m to protect water quality (NRCS, 1997), which is sufficient for sediment trapping.

Although sediment trapping efficiency is significantly affected by buffer width, there is still a lack of comprehensive understanding of the relationships between buffer width and trapping efficiency despite this ample research. Although attempts made to use the buffer width as a predictor for sediment trapping efficiency was not very successful (Figure 1), the analysis does point out that the sediment trapping efficiency was at least 80% for all buffer widths of greater than approximately 5 m. Case studies are still the primary source of information for buffer width comparisons and planning.

Sediment trapping efficiency is also affected by slope, but the overall relationship is not consistent among studies. Overall, sediment trapping efficiency did not vary by vegetation type and grass buffers and forest buffers have roughly the same sediment trapping efficiency. Among grass buffer strips, switchgrass buffer strips seem more efficient in trapping sediment than fescue FS and cool-season grasses, but less efficient than big bluestem and eastern gamagrass.

Sediment trapping potential of riparian buffers is also related to sediment particle size. Since sediment trapping efficiency is reduced as sediment size decreases (Lee *et al.*, 2000). Several authors concluded that more than 95% of the aggregates larger than 40 μm in diameter could be captured in the first 5 m of the buffer (White *et al.*, 2007). This suggests that trapping efficiency depends on soil type from which the sediment is produced and rainfall energy as a primary source of aggregate dispersion. Studies also found that the performance of FS for reducing sediment was significantly affected by runoff flow conditions and FS are less effective in reducing sediment transport under concentrated flow conditions.

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Appendix A. Summary table of buffer effectiveness in trapping sediment by buffer width, vegetation type, soil type, slope, and rainfall (runoff)
.

Vegetation type	Sediment (Mg ha^{-1} or mgl^{-2})		Buffer characteristics			Percent reduction in load	Rainfall			Study
	Inflow	Outflow	width (m)	soil	slope		Intensity (mm h^{-1})	Amount (mm)	Runoff (mm h^{-1})	
Switchgrass	NA	NA	3	Coland silty clay loam	3%	0·69	51	51	11·2	Lee *et al*. (1999)
	NA	NA	6	—	3%	0·78	51	51		Lee *et al*. (1999)
	0·0343[1]	0·0104[1]	7·1	—	5%	0·7	25	50		Lee *et al*. (2000)
	0·4838[1]	0·1459[1]	7·1	—	5%	0·7	69	69		Lee *et al*. (2000)
	NA	NA	7·1	—	5%	0·95	Natural	rainfall		Lee *et al*. (2003)
	10·6[1]	0·9[1]	0·7	Mexico silt loam	5%	0·92	66	66		Blanco-Canqui *et al*. (2004a)
	13·6[1]	0·96[1]	0·7	Mexico silt loam	5%	0·93	66	66	C*	Blanco-Canqui *et al*. (2004b)
	NA	NA	0·72	Monona silt loam	8–16%	0·63	64	64		Gilley *et al*. (2000)
	NA	NA	0·14	Bubbs I sandy loam	5%	0·39			1·31	Meyer *et al*. (1995)
						0·29			2·62	
	NA	NA	0·2	Bubbs I sandy loam		0·61			0·66	Meyer *et al*. (1995)
						0·46			1·31	
						0·35			1·97	
						0·35			2·62	
	NA	NA	0·31	Bubbs II sandy loam	5%	0·79			0·33	Meyer *et al*. (1995) concentrated flow condition
						0·75			0·66	
						0·73			0·98	
						0·67			1·31	
						0·66			1·64	
						0·63			1·97	
						0·60			2·29	
						0·60			2·62	

	NA	NA	0·76	Bubbs I sandy loam	5%	0·62			0·66	Meyer *et al.* (1995)
						0·48			1·31	
						0·36			1·97	
						0·43			2·62	
	2·85[1]	0·83[1]	0·3	Brooksville silty clay	3%	0·71	Natural	Rainfall		Rankins *et al.* (2001)
Vetiver grass hedges	NA	NA	0·2	Bubbs I sandy loam	5%	0·6			0·66	Meyer *et al.* (1995)
						0·5			1·31	
						0·5			1·97	
						0·34			2·62	
	NA	NA	0·2	Bubbs II sandy loam	5%	0·78			0·66	
						0·74			1·31	
						0·67			1·97	
						0·64			2·62	
Vetiver hedges	NA	NA	15	Krasnozems clay	15%	0·65	Natural	Rainfall		McKergow *et al.* (2004)
Miscanthus	NA	NA	0·15	Bubbs I sandy loam	5%	0·24	NA	NA	1·31	Meyer *et al.* (1995)
	NA	NA	0·3	Providence silt loam	5%	0·71	NA	76		McGregor *et al.* (1999)
	NA	NA	0·3		5%	0·78	NA	64		
	NA	NA	0·3		5%	0·66	Natural	Rainfall		
Big bluestem	2·85[1]	0·57[1]	0·3	Brooksville silty clay	3%	0·80	Natural	Rainfall		Rankins *et al.* (2001)
Eastern gamagrass	2·85[1]	0·62[1]	0·3	Brooksville silty clay	3%	0·78	Natural	Rainfall		Rankins *et al.* (2001)
Cool-season grass	NA	NA	3	Coland silty clay loam	3%	0·62	51	51		Lee *et al.* (1999)
	NA	NA	6	—	3%	0·75	51	51		Lee *et al.* (1999)
	4433[2]	51[2]	15·3	Hobbs silt loam	4%	0·99		40–65		Mankin *et al.* (2007)
Fescue filter strip	10·2[1]	2·0[1]	0·7	Mexico silt loam	5%	0·8	66	66		Blanco-Canqui *et al.*, 2004a
	10·2[1]	0·7[1]	4·0	—	5%	0·93	66	66		

(*continued overleaf*)

Appendix A. (*Continued*).

Vegetation type	Sediment (Mg ha^{-1} or mgl^{-2})		Buffer characteristics			Percent reduction in load	Rainfall			Study
	Inflow	Outflow	width (m)	soil	slope		Intensity (mm h^{-1})	Amount (mm)	Runoff (mm h^{-1})	
	10·2[1]	0·3[1]	8·0	—	5%	0·97	66	66		
	13·2[1]	3·74[1]	0·7	—	5%	0·72	66	66	C*	
	13·2[1]	1·23[1]	4·0	—	5%	0·91	66	66	C*	
	13·2[1]	0·38[1]	8·0	—	5%	0·97	66	66	C*	
	NA	NA	0·28	Dubbs I sandy loam	5%	0·45			0·66m^3 min^{-1} m (C*)	Meyer *et al.* (1995)
	NA	NA	0·28	—	5%	0·33			1·31	
	NA	NA	0·28	—	5%	0·23			1·97	
	NA	NA	0·28	—	5%	0·15			2·62	
Fescue filter strip	2·85[1]	0·96[1]	0·3	Brooksville silty clay	3%	0·66	Natural	Rainfall		Rankins *et al.* (2001)
	NA	NA	4·6	Woodstown sandy loam	3%	0·52	48·3	48·3		Magette *et al.* (1989)
	NA	NA	9·2		3%	0·75	48·3	48·3		
	NA	NA	3	Cecil sandy loam to clay loam	4·9%	0·38	Natural	Rainfall		Daniels and Gilliam (1996)
	NA	NA	6		4·9%	0·68	Natural	Rainfall		
	NA	NA	3		2·1%	0·44	Natural	Rainfall		
	NA	NA	6		2·1%	0·56	Natural	Rainfall		
Bermudagrass	NA	NA	8	Alpha loamy sand	3·5%	0·8	Natural	Rainfall		Sheridan *et al.* (1999)
	NA	NA	0·6	Lexington silt loam	10%	0·67	64	128		Raffaelle *et al.* (1997)
Orchardgrass filter strip	2·1[1]/3538[2]	0·36[1]/1792[2]	4·6	Groseclose silt loam soil	5%	0·83	50	50		Dillaha *et al.* (1989)
	2·1[1]/3538[2]	0·14[1]/582[2]	9·1	—	5%	0·93	50	50		—
	3·93[1]/5513[2]	0·56[1]/676[2]	4·6	—	11%	0·86	50	50		—
	3·93[1]/5513[2]	0·10[1]/354[2]	9·1	—	11%	0·97	50	50		—
	8·94[1]/15929[2]	4·22[1]/6063[2]	4·6	—	16%	0·53	50	50		—
	8·94[1]/15929[2]	2·71[1]/3404[2]	9·1	—	16%	0·7	50	50		—
Bromegrass filter strip	NA	NA	3·0	Fayette silt loams	7%	0·7	Natural	Rainfall		Robinson *et al.* (1996)
	NA	NA	3·0	—	12%	0·8	Natural	Rainfall		

	NA	NA	9·1	—	7%	0·85	Natural	Rainfall		
	NA	NA	9·1	—	12%	0·85	Natural	Rainfall		
Switchgrass plus fescue filter Strip	10·8[1]	0·4[1]	0·7 + 3·3	Mexico silt loam	5%	0·96	66	66		Blanco-Canqui *et al*. (2004a)
	10·8[1]	0·2[1]	0·7 + 7·3	—	5%	0·98	66	66		
	13·6[1]	0·39[1]	0·7 + 3·3	—	5%	0·97	66	66	C*	Blanco-Canqui *et al*. (2004b)
	13·6[1]	0·11[1]	0·7 + 7·3	—	5%	0·99	66	66	C*	
Switchgrass plus natural grass strip	10·3[1]	0·7[1]	0·7 + 3·3	—	5%	0·93	66	66		Blanco-Canqui *et al*. (2004a)
	10·3[1]	0·2[1]	0·7 + 7·3	—	5%	0·98	66	66		
Fescue filter strip plus groundcover	NA	NA	5	Cecil sandy loam to clay loam	3·3%	0·5				Daniels and Gilliam (1996)
	NA	NA	13	—	3·3%	0·9				
Forest filter strip	NA	NA	10	Silt loam	1–2%	0·72	NA	NA	155 l min^{-1}	White *et al*. (2007)
	NA	NA	10	Sandy loam	5–7%	0·67	NA	NA	184 l min^{-1}	
	NA	NA	10	—	10–12%	0·65	NA	NA	193 l min^{-1}	
	NA	NA	10	—	15–17%	0·86	NA	NA	180 l min^{-1}	
	NA	NA	10	—	20–22%	0·79	NA	NA	204 l min^{-1}	
Giant cane filter strip	NA	NA	3·3	Hayond silt loam	1%	0·94	Natural	Rainfall		Schoonover *et al*. (2006)
	NA	NA	6·6	—	1%	0·89	Natural	Rainfall		
	NA	NA	10·0	—	1%	1·00	Natural	Rainfall		
Mixed deciduous forest buffer	NA	NA	3·3	—	1%	0·50	Natural	Rainfall		
	NA	NA	6·6	—	1%	0·86	Natural	Rainfall		
	NA	NA	10·0	—	1%	0·76	Natural	Rainfall		

(*continued overleaf*)

Appendix A. (*Continued*).

Vegetation type	Sediment (Mg ha^{-1} or mgl^{-2})		Buffer characteristics			Percent reduction in load	Rainfall			Study
	Inflow	Outflow	width (m)	soil	slope		Intensity (mm h^{-1})	Amount (mm)	Runoff (mm h^{-1})	
5 m cool-season grasses plus 4·7 m plum shrub	4433[2]	122[2]	9·7	Hobbs silt loam	3·9%	0·99		40–65		Mankin *et al.* (2007)
5 m switchgrasses plus 7·3 m plum shrub	4433[2]	109[2]	12·3	Hobbs silt loam	3·8%	0·99		40–65		Mankin *et al.* (2007)
7·1 m switchgrass plus 9·2 m m woody plant	0·0343[1]	0·0021[1]	16·3	Coland silty clay loam	5%	0·94	25	50		Lee *et al.* (2000)
	0·4838[1]	0·0388[1]	16·3		5%	0·92	69	69		Lee *et al.* (2000)
	NA	NA	16·3		5%	0·97	Natural	Rainfall		Lee *et al.* (2003)
Fescue filter strip plus groundcover	NA	NA	7	Cecil sandy loam to clay	3·3%	0·73	Natural	Rainfall		Daniels and Gilliam (1996)
	NA	NA	18		3·3%	0·82	Natural	Rainfall		
Tree-grass-tree	NA	NA	6	Fulvi-calcaric Cambisol	1·8%	0·92	Natural	Rainfall		Borin *et al.* (2005)

* C refers to concentrated flow: means the soil in the column is the same as above column. Under sediment column, the number [1] has units of Mg ha^{-1} and the number [2] has units of mg l^{-1}, NA means data were not available for reporting.