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Buffers and Vegetative Filter Strips

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This chapter describes the use of buffers and vegetative filter strips relative to water quality. In particular, we primarily discuss the herbaceous components of the following NRCS Conservation Practice Standards:

Filter Strip (393)
Riparian Forest Buffer (391)
Conservation Cover (327)
Contour Buffer Strips (332)
Alley Cropping (311)
Vegetative Barrier (601)
Riparian Herbaceous Cover (390)
Grassed Waterway (412)

Placement of most of these practices is illustrated in figure 4-1. Common purposes of these herbaceous components (as defined by the NRCS Conservation Practice Standards) are to:

- Reduce the sediment, particulate organics, and sediment-adsorbed contaminant loadings in runoff.
- Reduce dissolved contaminant loadings in runoff.
- Serve as Zone 3 of a riparian forest buffer.
- Reduce sediment, particulate organics, and sediment-adsorbed contaminant loadings in surface irrigation tailwater.
- Restore, create, or enhance herbaceous habitat for wildlife and beneficial insects.
- Maintain or enhance watershed functions and values.
- Reduce sheet and rill erosion.
- Convey runoff from terraces, diversions, or other water concentrations without causing erosion or flooding (grassed waterway).
- Reduce gully erosion (grassed waterway and vegetative barrier).

The term buffer is used here to generally refer to all eight practice standards noted above. These can be further identified as "edge-of-field" and "in-field" buffers consistent with the terminology used by Dabney et al. (2006). Edge-of-field buffers include filter strips, riparian forest buffers, and riparian herbaceous cover. In-field buffers include conservation cover, contour buffer strips, alley cropping, and grassed waterways. Vegetative barriers could be either in-field or edge-of-field buffers.

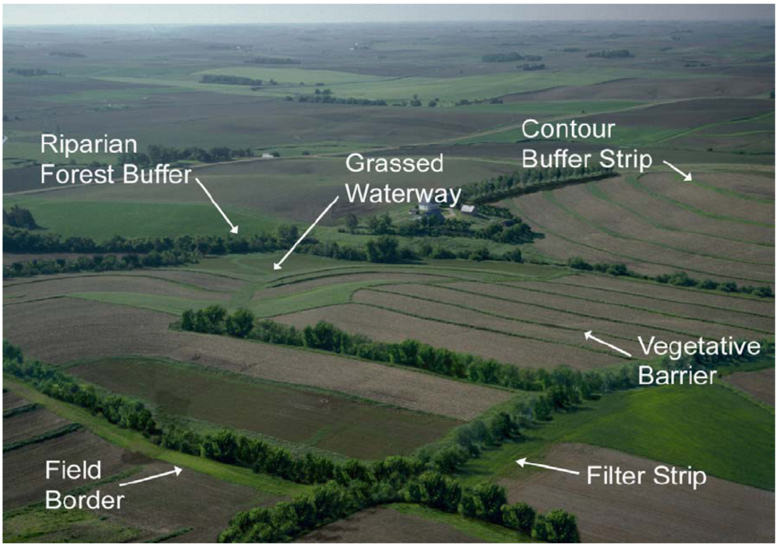

Figure 4-1. Illustration of several vegetative buffer types (photo courtesy of USDA-NRCS).

Processes that influence the environmental impacts provided by these practices include water infiltration, particulate deposition, possible adsorption of soluble pollutants to vegetation and in-place soil, and increased resistance to erosion. Vegetative buffers tend to reduce flow velocities because the vegetation in the buffer provides greater resistance to water flow. This reduction in flow velocity causes deposition of some of the suspended particulates, and the increased resistance to flow can also cause ponding along the upstream edge of the buffer, which promotes infiltration of water and deposition of particulates exiting the field area. Infiltration also takes place within the buffer, which leads to an overall reduction in outflow of water and other contaminants. Together, reduced flow velocity and increased infiltration can offer water quality improvement benefits. Buffers can also promote the uptake of nutrients, denitrification, and assimilation/transformation on the surface of soil, vegetation, and debris. Additionally, there may be a dilution effect on pollutants in the water transported through the buffer due to rainfall interception by the buffer. Another mechanism by which buffers provide water quality improvement is through reduced erosion, since the dense, perennial vegetation generally provides greater resistance to erosion.

Flow conditions vary for the different buffer types. For low flow conditions, the vegetation is expected to remain unsubmerged, but at higher flows the vegetation will be submerged. Of the buffer types described above, grassed waterways are intended to have submerged conditions when functioning in field conditions (Dabney, 2003). As a result, the flow rate entering a buffer system is of primary importance in the functioning of the buffer system. In particular, the flow rate per unit width entering or flowing through the buffer system will affect whether the vegetation is submerged or unsubmerged. The conditions under which vegetation becomes submerged depend on the physical characteristics of the vegetation, including the height, stem density, and stiffness of the vegetation. Dabney (2003) uses specific flow rate (product of flow velocity and depth) to highlight the range of applicability of various buffer systems. Using this method, the specific flow rate range for filter strip type systems is less than approximately 0.22 $ft^2\ s^{-1}$, and the range for grassed waterways is greater than this. Vegetative barriers have specific flow rates that span the range between filter strips and grassed waterways.

Potential Impacts

Surface Processes

Researchers have conducted extensive studies on the pollutant trapping capability of buffers (edge-of-field buffers) where the vegetation has remained unsubmerged. Much of this research has been performed on plot-scale buffer systems. Reported sediment trapping efficiencies have ranged from 41% to 100%, and infiltration efficiencies have ranged from 9% to 100% (Arora et al., 1993; Arora et al., 1996; Barfield et al., 1998; Coyne et al., 1995; Coyne et al., 1998; Daniels and Gilliam, 1996; Dillaha et al., 1989; Hall et al., 1983; Hayes and Hairston, 1983; Lee et al., 2000; Magette et al., 1989; Munoz-Carpena et al., 1999; Parsons et al., 1990; Parsons et al., 1994; Patty et al., 1997; Schmitt et al., 1999; Tingle et al., 1998).

Numerous studies have also examined the nutrient trapping effectiveness of buffers. Dosskey (2001) summarized many of these studies. The buffer trapping efficiency of total phosphorus ranged from 27% to 96% (Dillaha et al., 1989; Magette et al., 1989; Schmitt et al., 1999; Lee et al., 2000; Uusi-Kamppa et al., 2000). The reduction in nitrate-nitrogen (nitrate) ranged from 7% to 100% (Dillaha et al., 1989; Patty et al., 1997; Barfield et al., 1998; Schmitt et al., 1999; and Lee et al., 2000).

As mentioned above, many of the studies on buffer performance have been performed on plot-scale systems. In most of these studies, the ratio of drainage area to buffer area has generally been small, which would be expected to reduce the flow rate per unit width entering the buffer. Thus, this reduced ratio would be expected to reduce the overall loading and loading rate of water and pollutants to the buffer system compared to a case with a greater ratio. In many cases, the ratio of drainage area to buffer area was smaller than might be expected in typical applications. The drainage area to buffer area ranged from 50:1 to 1.5:1 in numerous studies, including those by Arora et al. (1993), Arora et al. (1996), Barfield et al. (1998), Coyne et al. (1995), Coyne et al. (1998), Daniels and Gilliam (1996), Dillaha et al. (1989), Hall et al. (1983), Hayes and Hairston (1983), Lee et al. (2000), Magette et al. (1989), Munoz-Carpena et al. (1999), Parsons et al. (1990), Parsons et al. (1994), Patty et al. (1997), Schmitt et al. (1999), and Tingle et al. (1998).

Of these studies, 50% have a drainage area to buffer area ratio of less than 5:1, whereas a drainage area to buffer area ratio of greater than 20:1 can be expected under most field conditions. For studies with a drainage area to buffer area ratio greater than 10:1 (Arora et al., 1996; Arora et al., 1993; Daniels and Gilliam, 1996; Schmitt et al., 1999; Tingle et al., 1998), the sediment trapping efficiency ranged from 41% to 95%. For a drainage area to buffer area ratio of greater than 10:1, the infiltration ratios ranged from 9% to 98% (Arora et al., 1996; Schmitt et al., 1999). A modeling study showed that higher ratios are expected to produce lower trapping efficiencies (Dosskey et al., 2002). Based on guidelines from the NRCS (1999), the ratio of the drainage area to the buffer area should be 70:1 to 50:1, depending on the RUSLE-R factor in the region. Due to uneven flow distribution, it is likely that the drainage area to a specific region of the buffer will vary with position along the length of the filter. As a result, the drainage area to buffer area ratio will vary, and the areas with the greatest ratio may be contributing the majority of the flow to the system and may need to be considered in the design of a buffer system.

While most studies have been on plot-sized, controlled buffers, the few studies that have investigated unbordered field-scale buffers have shown similar results. Daniels and Gilliam (1996) found that over a range of rainfall events, the buffer reduced sediment loads by 60% to 90%, runoff loads by 50% to 80%, and total phosphorus loads by 50%. The retention of soluble phosphorus was about 20%. The retention of ammonium-nitrogen was 20% to 50%, and the retention of total nitrogen and nitrate was approximately 50%. Sheridan et al. (1999) investigated runoff and sediment transport across a three-zone riparian forest buffer system and monitored the outflow from each zone. Their study showed that runoff reduction in the grass buffer averaged 56% to 72%, and the reduction in sediment transport across the grass buffer ranged from 78% to 83%. They observed no evidence of concentrated flow in the grass buffer portion of their study during the four-year duration of the project, despite a period of high rainfall that included a 100-year, 24-hour storm event. Helmers et al. (2005a) found an average sediment trapping efficiency of 80%.

While the drainage area to buffer ratio captures one source of variability that can affect buffer performance, other variables include condition of the upslope area, degree to which flow concentrates in the upslope area, and the size of the storm event (Lee et al., 2003; Dosskey et al., 2002; Helmers et al., 2002). In some cases, narrow buffers have been shown to provide significant benefits. Narrow buffers (<3 ft.), such as vegetative barriers (in-field and edge-of-field buffers), have been shown to trap significant amounts of sediment (Van Dilk et al., 1996; Blanco-Canqui et al., 2004) and soluble nutrients under conditions where infiltration is increased (Eghball et al., 2000). Gilley et al. (2000) studied the performance of these types of systems under no-till management conditions and found 52% less runoff and 53% less soil loss on plots with grass hedges versus plots without grass hedges. These systems are narrow grass hedges planted on the contour along a hillslope. These hedges normally use stiff-stemmed grasses to reduce overland flow velocity and promote sediment deposition. Grassed hedges are another management practice that has water quality benefits, but their performance will likely be directly tied to how well the vegetation is maintained within the grass hedge. Again, this practice is applicable over a wider range of flow conditions than a buffer, which is intended to intercept shallow overland flow, since grass hedges are designed to control concentrated flow erosion. So, while the drainage area into the buffer is important, the performance of narrow grass hedges highlights that a continuous, well maintained buffer edge may be just as important for maximizing the water quality benefits of these systems.

Research has shown that buffers can remove significant quantities of sediment and nutrients as well as infiltrating a significant portion of the inflow. The reduction in sediment may be generally around 50% for many field settings where the buffer integrity is maintained, but there is likely to be significant variability in the performance of these systems. In general, nutrients that are strongly bound to sediment, such as phosphorus, will have reductions lower than but similar to sediment reductions, but dissolved nutrients will have lower reductions, and their reduction will be closely tied to infiltration. Buffers will likely be less effective for nutrient trapping than for sediment trapping. Daniels and Gilliam (1996) noted that even though buffers are an accepted and highly promoted practice, little quantitative data exist on their effectiveness under unconfined flow-path conditions.

A significant unknown relative to the performance of buffers is how effective they are when flow begins to concentrate and how much of the buffer is effective in treating overland flow. A study by Dosskey et al. (2002) attempted to assess the extent of concentrated flow on four farms in southeast Nebraska and its subsequent impact on sediment trapping efficiency. From visual observations, the researchers estimated an effective buffer area and gross buffer area. The gross buffer area was the total area of the buffer, and the effective buffer area was the area of the buffer that field runoff would encounter as it moved to the stream. Their study showed the effective area, as a percent of the gross area, ranging from 6% to 81%. The modeled sediment trapping efficiency ranged from 15% to 43% for the effective area, compared to 41% to 99% for the gross area. By modeling sediment trapping in a buffer, Helmers et al. (2005b) found that as the convergence of overland flow increases, sediment trapping efficiency is reduced. This concentration of flow, in addition to increasing the flow rate in portions of the buffer that receive runoff, would be expected to adversely affect the overall infiltration and soluble pollutant trapping of the system. Results from these studies show that concentrated flow can reduce the effectiveness of buffers and should be considered in their design. That is, the placement of a buffer may need to be carefully considered so that overland flow is intercepted before it converges or is run through an artificial mechanism to distribute it more evenly for maximum performance. One technique is to use vegetative barriers on the upslope edge of buffers to distribute flow. Another approach is to place vegetative barriers on the contour within the field to minimize the occurrence or magnitude of concentrated flow.

Although grassed waterways (in-field buffers) have been widely used as part of conservation systems, few studies have quantified the reduction in runoff volume and velocity along with sediment delivery through grassed waterways (Fiener and Auerswald, 2003). A study by Briggs et al. (1999) found that grassed waterways reduced the volume of runoff by 47% when compared to non-grassed waterways. Hjelmfelt and Wang (1999) modeled conditions in Missouri for their study. Their data show that a 1,970 ft. grassed waterway with a width of 33 ft reduced the overall volume of runoff by 5%, peak runoff rates by 54%, and sediment yield by 72%.

Another important contribution that grassed waterways and vegetative barriers can provide is protection against gully erosion within agricultural fields. Gully erosion may occur as a result of flow concentration on the landscape. The vegetation in the waterway provides greater resistance to erosion if properly designed. If a waterway can be protected from erosion, then the allowable velocity can be increased. Vegetating the waterway is one form of protection (Haan et al., 1994). In many areas, reducing ephemeral gully erosion can have a significant impact on water quality. Based on studies in 19 states, the USDA (1996) reported that ephemeral gully erosion as a percentage of sheet and rill erosion ranged from 21% to 275%. So, being able to reduce gully erosion would be expected to have a positive impact on downstream water quality, particularly turbidity caused by sediment and phosphorus loss from surface erosion.

Subsurface Processes

While surface water processes are important in evaluating the benefits of buffer systems, they can also intercept shallow groundwater and remove nutrients. Nutrient removal, particularly nitrate removal from shallow groundwater, is one of the common attributes of riparian forest buffers, but clearly not all are equal in this regard. Hill (1996) determined that most riparian forest buffers that remove large amounts of nitrate occur in landscapes with impermeable soil layers near the ground surface. In this setting, nitrate-enriched groundwater from agriculture follows shallow flow paths that increase contact with higher organic matter surface soil and roots of vegetation (Groffman et al., 1992; Hill, 1996). Studies have shown that riparian areas with higher transport rates for subsurface flow (usually with steep terrain and high transmissivities for soils) have the least nitrate attenuation and probably the least denitrification (Jordan et al., 1993).

Denitrification, the microbially mediated reduction of nitrate to nitrogen gases, is an important mechanism for removal of nitrate from groundwater in vegetative buffers (Vidon and Hill, 2004). Denitrification has been measured in a few restored buffers, but in general most of the data come from naturally occurring riparian forests. Denitrification has been measured in riparian and swamp forests in at least 18 different studies, mostly in temperate regions. Not all of the studies were conducted in agricultural watersheds, but there does not seem to be a pattern of the agriculturally impacted riparian areas having higher rates. Rates in the range of 27 to 79 lb N ac^{-1} $year^{-1}$ are not uncommon for these studies, but very low rates in the 0.89 to 4.5 lb N ac^{-1} $year^{-1}$ range are also evident. These studies include a wide variety of systems, ranging from grass buffer areas at field edges to swamp forests. In general, the highest rates were measured from soils of wetter drainage class more highly loaded with N. Nitrogen removal through vegetation assimilation is clearly important (Lowrance et al., 1984), but maintaining assimilation rates requires active management of vegetation.

The capacity of buffers restored on previously cropped soils to remove nitrate is the subject of ongoing studies within the Bear Creek watershed in central Iowa (Simpkins et al., 2002). A focus of these efforts has been to document the capacity of riparian zones to remove nitrate-nitrogen and to elucidate controlling factors. Nitrate-removal efficiency was found to vary between 25% and 100%, with mean nitrate-removal efficiencies ranging from 48% to 85% in shallow groundwater under re-established riparian buffers (Simpkins et al., 2002). The hydrogeologic setting, specifically the direction of groundwater flow and the position of the water table in thin sand aquifers underlying the buffers, is probably the most important factor in determining buffer efficiency (Simpkins et al., 2002). Residence time of groundwater and populations of denitrifying bacteria in the buffer may also be important. Buffer age does not appear to affect removal efficiency. Heterogeneity and larger hydrologic controls will pose challenges to predicting the groundwater quality impacts of future buffers in the watershed.

Factors Impacting Buffer Effectiveness

Buffer Design

Buffers are typically installed with a fixed width. However, due to landscape topography, there are often areas of a buffer that receive greater loading. Bren (1998) proposed using a design procedure in which each element of the buffer has the same ratio of upslope-to-buffer area so that the load to the buffer is constant. Tomer et al. (2003) used terrain-analysis techniques for development of best-management-practice placement strategies, placing buffers according to wetness indices to guarantee that buffer vegetation would intercept overland flow from upslope areas. Since it is unlikely that flow entering the upstream edge of a buffer will be uniformly distributed, it is important to continue to investigate design methods that can maximize the overall effectiveness of the buffer by ensuring that overland flow moves through the buffer. While present buffer designs generally use a fixed-width buffer, consideration should be given to future designs that incorporate variable-width buffers based on the upland contributing area. This may be particularly important where maximizing infiltration is important for reducing soluble pollutant loads to waterbodies.

As with most management practices, there is a time lag with buffers before these systems perform as designed. This time lag depends on how quickly a dense stand of vegetation can be established. There could be much grass growth in a single growing season. However, to ensure long-term performance of the system, it is important to both establish a vigorous and dense stand of vegetation and to maintain the vegetative stand after it is established. The integrity of the buffer system is likely more important than its age in evaluating the effectiveness of the system; thus, some of the benefits could be observed in what may be considered a relatively short time frame.

Site Characteristics

Research has shown that buffers provide water quality benefits, but there is a significant range in the performance of these systems. The performance depends on the field, topographic, and climatic conditions at the site. As discussed above, while there is a significant body of information on the performance of buffers under fairly controlled situations, there is much less information available on the in-field performance of these systems. While it is expected that there will still be significant water quality benefits under these field conditions, it is likely that the performance will be reduced as compared to the results from controlled experiments. In designing buffer systems, the site conditions should be considered to maximize overland flow through the buffer and shallow groundwater interaction with the buffer to take full advantage of the capabilities of the system. While the ratio of drainage area to buffer area and the width of the buffer are factors that can affect the overall performance of the system, research has shown that narrow buffers are also very effective, and some of the most important factors in the performance of the system are the integrity, density, and continuity of the buffer. One of the most important factors to consider in designing or maintaining a buffer is that concentrated flow should be minimized. One method to do this is to ensure that the buffer edges have dense vegetation, which tends to distribute flow.

Since the mechanisms for reducing pollutant transport in buffers ranges from deposition to infiltration, there are numerous factors that influence the physical performance of the buffer regardless of flow concentration. Some of the most sensitive parameters for the hydrologic processes in a buffer include initial soil water content and vertical saturated hydraulic conductivity (Munoz-Carpena et al., 1999). For sediment trapping, some of the most sensitive parameters include the sediment characteristics (particles size, fall velocity, and sediment density) as well as the grass spacing, which affects the resistance to overland flow (Munoz-Carpena et al., 1999). These factors highlight the importance of having a dense stand of vegetation to maximize the pollutant trapping capacity of the buffer.

Soils that have a greater capacity to infiltrate runoff water are likely to have better performance, especially for reducing the mass export of soluble pollutants from surface water runoff. In addition, the sediment trapping capability is greater for larger particles. Thus, when evaluating buffer performance, the eroded (aggregated) sediment size distribution is important. There is a research need for additional data to improve eroded aggregate size distribution predictions as well as for predicting the nitrogen and phosphorus content of each sediment size fraction.

As described previously, the loading, or more specifically the loading rate to the system, will also impact the performance of the system. Some of the variables that influence loading include soil, topography, and management of the upland area. Helmers et al. (2002) found the sediment trapping efficiency to be negatively impacted by the slope of the contributing area, since the higher slopes (10% versus 2%) had greater flow rates entering the buffer system. They also found that as the storm size increased, the sediment trapping efficiency of the buffer decreased. Both of these factors (slope and storm size) influenced the loading, including the flow rate, to the buffer, so as the loading or loading rate increased, the percentage efficiency decreased. However, even though the percent reduction may decrease, the overall mass trapped in the buffer would likely be significant.

Since grassed waterways are designed to convey water off the landscape, such a system must be designed to effectively convey water off the landscape while minimizing channel instability. The hydrology of the site and the soils, particularly in the area of the grassed waterway, need to be considered so that water conveyance is maintained while flow velocities are minimized. While grassed waterways are mainly designed to convey water, as discussed previously, there are also some runoff reduction and direct water quality benefits from grassed waterways. This reduction in runoff will likely be greater under smaller storm and runoff conditions, when the specific flow rate in the grassed waterway is in the range commonly expected for other buffer systems. During larger precipitation events, the grassed waterway will likely function only in a water conveyance capacity.

Limitations on Impact

A large percentage of crop land would benefit from the use of buffers. The scenarios where they would not be expected to have a direct impact on water quality are where there is little runoff and resulting pollutant movement and where the buffer would not intercept shallow groundwater. From a review of the literature, it is evident that buffers provide water quality benefits. However, the effectiveness of buffers will vary significantly depending on the flow conditions in the buffer (e.g., the concentration of flow) as well as the area of the buffer that overland flow will encounter. There is a need to better understand the in-field performance of buffers, where buffer integrity may be comprised by lack of vegetation or features that allow bypass flow to occur through the buffer. Such research would provide much needed information on the performance of this conservation practice under likely common field conditions. This would allow for better evaluation of the range of expected performance. In addition, there are questions about the maintenance required to maximize the performance of the buffer. Most monitoring studies have been short-term in nature, and the long-term performance of buffers with and without some level of maintenance is relatively unknown.

From the review of the literature relative to grassed waterways, it is apparent that only a few studies have quantified the environmental performance of this practice. Differences in grassed waterway design, vegetative conditions, and upland field conditions along with limited data collection make such work difficult. However, the literature also shows that these practices can have a positive impact on water quality and can be effective in reducing peak discharge and sediment yield. Grassed waterways likely improve the quality of the water that enters the channel, and they can also prevent further water quality degradation by reducing ephemeral gully erosion. The available research also indicates positive effects on reducing the volume of runoff. Further investigations in all of these areas are desirable. In particular, there is a need to better understand channel/gully processes, how they contribute to overall delivery of sediment and nutrients to downstream waterbodies, and how practices such as vegetative barriers and grassed waterways can be used to reduce pollutant loading from these mechanisms. While it would be difficult to estimate the direct benefit to water quality improvement on a broad scale, these systems would be expected to be directionally correct. And we know that there is a direct environmental benefit through the reduction in gully erosion with the use of grassed waterways, provided that the waterway is maintained so there is no short-circuiting of flow along the edge of the grassed waterway.

Another area that is in need of future studies is quantifying the percentage of shallow groundwater moving to a particular stream that interacts with the buffer zone. A specific type of landscape in which this might be important is where an extensive subsurface tile drainage system short-circuits subsurface flow through a buffer to streams. Under these conditions, the quantity of shallow groundwater interacting with the root zone of the buffer is likely to be greatly reduced. This effect should be acknowledged in the design, and another conservation practice may be better suited for treating this water. In particular, an edge-of-field practice, such as a wetland, may be more effective in treating the water exiting the subsurface tile lines. In addition, in areas where significant subsurface drainage is present, there may be backslopes on some of the streams or drainage ditches that prevent overland flow from uniformly entering the stream. Instead, the overland flow may flow to a low area and then enter the drain through this pathway, thereby reducing contact with the buffer and the effectiveness of the system. This should be considered when designing the buffer system.

Cost:Benefit Analyses

The costs associated with buffer practices are directly tied to the land that is taken out of production. In some instances, this land could be productive farmland. As such, there is some negative attitude toward installation of these systems. However, a yield reduction in the remainder of the adjacent agricultural land is not expected. Having additional field-scale performance data, particularly where surface water flow concentrates, may improve the acceptance with some producers. Qiu (2003) studied the cost-effectiveness of installing buffers on two small watersheds in Missouri, considering a ten-year evaluation horizon and considering the private costs associated with land opportunity cost and buffer installation cost. For this scenario, the annualized cost of the buffer was \$62.40 ac^{-1} and the annualized benefit was \$73.30, which includes CRP land rental rate and 50% cost share for the installation. For this case, where there was a government subsidy to the producer, there was a net benefit to the producer, so the cost of land taken out of production should be balanced against the value of "green" payments that may offset the cost.

Yuan et al. (2002) studied the cost-effectiveness of various agricultural BMPs in the Mississippi Delta. For their case study, with conventional tillage, they found that edge-of-field buffers reduced sediment yield from 4.5 to 3.7 t ac^{-1} $year^{-1}$ (18% reduction) through the use of filter strips. The approximate cost of sediment reduction for this tillage condition was \$8.5 t^{-1}. When no-till was considered, the reduction in sediment yield due to vegetative filter strips was reduced from 2.2 to 1.6 t ac^{-1} $year^{-1}$ (26% reduction), and the cost of sediment reduction was \$11.8 t^{-1}. Using estimated sediment, total nitrogen, and total phosphorus losses for different tillage practices from chapter 9 of this book and estimated trapping efficiencies for buffers under common field-scale scenarios, the approximate cost per unit reduction in sediment and nutrients is shown in table 4-1. This is a simplified analysis since the cost associated with the practice is just the land rental rate, which was about \$135 ac^{-1} in Iowa in 2005 (ISU Extension, 2005). Other costs would be associated with the buffer, but the major cost would be associated with the land out of production. This type of work highlights the need for establishing what the environmental benefits of these systems are on a field-scale, so that research may be able to help provide a basis for such "green" payments.

The National Conservation Buffer Initiative had a goal of 2 million miles of buffers installed on private land by 2002. Santhi et al. (2001) studied the economic and environmental benefits of this goal and of doubling the size of implementation. Their analysis likely did not consider the overall impacts of concentrated flow on the performance of buffer systems. However, their national estimated reductions in sediment loss, total nitrogen loss, and total phosphorus loss were 15.6%, 10.8%, and 11.7%, respectively, when considering the 2 million mile goal. When the goal was doubled to

Table 4-1. Cost estimates per unit of reduction in sediment, nitrogen, and phosphorus for buffers used in conjunction with two tillage systems.

Treatment System	Loss Estimates[a]	Reduction Range (%)		Pollutant Trapping Range		Annual Operating Cost[b] $(\$\ \mathrm{ac}^{-1})$	Cost Reduction	
		Low	High	Low	High		Low	High
Sediment	Soil loss (t ac^{-1} year^{-1})			(t ac^{-1} year^{-1})			per ton $(\$\ \mathrm{t}^{-1})$	
Typical	7.8	40	60	3.1	4.7	6.75	2.2	1.4
No-till	1	40	60	0.4	0.6	6.75	16.9	11.3
Total Nitrogen	N loss (lb ac^{-1} year^{-1})			(lb ac^{-1} year^{-1})			per lb $(\$\ \mathrm{lb}^{-1})$	
Typical	35.8	30	50	10.7	17.9	6.75	0.6	0.4
No-till	9.7	30	50	2.9	4.9	6.75	2.3	1.4
Phosphorus	P loss (lb ac^{-1} year^{-1})			(lb ac^{-1} year^{-1})			per lb $(\$\ \mathrm{lb}^{-1})$	
Typical	13.1	30	50	3.9	6.6	6.75	1.7	1.0
No-till	3.1	30	50	0.9	1.6	6.75	7.3	4.4

[a] Loss estimates from chapter 9 of this book.

[b] Assumes 5% of land area in buffer (cost is average land rental rate, $\$135\ \mathrm{ac}^{-1}$).

4 million miles, the national estimated reductions in sediment loss, total nitrogen loss, and total phosphorus loss were 28.9%, 27.2%, and 25.3%, respectively. While there are significant assumptions in developing these values, this analysis suggests the potential impact that buffer systems might have if 2 million miles or 4 million miles of buffers were installed. Santhi et al. (2001) also estimated the total net cost of these buffers, considering U.S. consumers' loss from reduced supply, program payments to landowners, federal technical assistance cost, and U.S. producers' net gain from higher prices due to the reduced supply. This net cost was then compared to the value of water quality improvements based on studies cited in Ribaudo et al. (1999). From this, Santhi et al. (2001) estimated that the annual net cost of the 2 million mile buffer goal was $793 million and the value of water quality improvements was $3,288 million, for a benefit:cost ratio of 4.1. When they increased the land enrolled in the program to 4 million miles, the cost increased to $1,302 million and the return from water quality improvements was estimated to be $5,650 million, for a benefit:cost ratio of 4.3. They concluded that their analyses showed the buffer programs to be cost-effective.

Interpretive Summary

Practice definition: Buffers and filter strips are areas of permanent vegetation located within and between cropland, grazing land, and disturbed land and the water courses to which they drain. These buffers are intended to intercept and slow runoff, thereby providing water quality benefits. In addition, in many settings, buffers are intended to intercept shallow groundwater moving through the root zone below the buffer.

Site/weather conditions that affect buffer effectiveness: The performance of buffer systems depends on the field, topographic, and climatic conditions at the site. In particular, these factors impact loading to the buffer system. Areas with steeper slopes and fewer in-field conservation practices can be expected to cause greater loading to the buffer. Therefore, the overall performance may be reduced when assessed on the quality of the water exiting the buffer. In addition, more extreme climatic conditions (i.e., greater and more intense precipitation) will also increase loading to the buffer system. However, buffers will still provide a water quality benefit even under more extreme conditions. Depending on site topography, surface water may concentrate prior to being intercepted by the buffer system, which will reduce buffer performance. In designing buffer systems, the potential concentration of surface water runoff should be considered, and to the extent possible, this occurrence should be mitigated by flow redistribution or by intercepting the flow prior to concentration. To maximize buffer performance, loading of water and pollutants should be limited through the use of in-field and edge-of-field conservation practices to maximize contact time with the buffer, and buffers should be properly maintained.

Summary of research findings: Buffers have been found to be most effective in trapping particulate pollutants. In addition, the export of soluble pollutants is expected to decrease when infiltration is maximized. Narrow buffers have also been shown to be effective in reducing the export of particulate pollutants when the integrity of the system is maintained. This highlights that one of the primary functions of buffers is to slow surface water movement, which reduces the export of pollutants, particularly particulate pollutants, and narrow strips of dense grass can function in this capacity and provide water quality benefits (Dabney et al., 2006). Narrow strips could also be used in-field as vegetative barriers to slow pollutant movement in-field and control concentrated flow erosion. To maximize infiltration of runoff, wider buffers or a greater buffer area to source area ratio should be used. Research has found a significant range in buffer performance, with reported sediment trapping efficiencies ranging from 41% to 100% and infiltration efficiencies ranging from 9% to 100%.

Buffers that interact with shallow groundwater moving through the root zone have been found to remove nitrate. Nitrate-removal efficiency has been found to vary between 25% and 100%, with mean nitrate-removal efficiencies ranging from 48% to 85% in shallow groundwater under re-established riparian buffers (Simpkins et al., 2002).

Cost of practice implementation: The costs of buffer systems are associated with the land taken out of production and with planting, establishing, and maintaining the buffers. The costs will vary with location, since land values vary. Qiu (2003) studied the cost-effectiveness of installing buffers on two small watersheds in Missouri, considering a ten-year evaluation horizon and considering the private costs associated with land opportunity cost and buffer installation cost. From this scenario, the annualized cost of the buffer was \$62.40 ac^{-1}.

Potential for water quality improvement: While buffer performance will vary depending on location due to site and climatic factors, research has shown that buffers can have a positive impact on water quality. Research has shown buffers to be most effective in trapping particulate pollutants, but they are also beneficial in reducing the export of soluble pollutants. Buffers are expected to reduce concentrations of nitrogen, phosphorus, and sediment in surface water runoff. In addition, when the buffer's root zone intercepts shallow groundwater, buffers have been shown to reduce nitrate-nitrogen concentrations through plant uptake. The ranges in water quality improvement have been found to vary significantly, but when buffers are designed and maintained properly, they may be expected to trap about 50% of incoming sediment, somewhat less for sediment-bound nutrients, and much less for dissolved nutrients. Nitrate-removal efficiency in shallow groundwater that interacts with the root zone of the buffer has been found to vary, but the mean efficiency may commonly be greater than 50%. However, the percent of groundwater interacting with the root zone of the buffer depends on the geologic and hydrologic conditions of the site and may be limited in cases where subsurface drainage systems short-circuit subsurface flow through the buffer.

In designing a buffer system, the flow contact of either surface water or groundwater with the buffer should be maximized, and the integrity of the vegetation in the buffer should be maintained. While buffers have the potential to provide significant water quality improvement, in-field management needs to be considered along with the implementation of other agricultural best management practices, since buffers best serve as polishers of the water moving through them.

Yuan et al. (2002) studied the cost-effectiveness of various agricultural best management practices (BMPs) in the Mississippi Delta. For their case study, with conventional tillage, they found that vegetative filter strips reduced sediment yield from 4.5 to 3.7 t ac^{-1} $year^{-1}$ (18% reduction). The approximate cost of sediment reduction for this tillage condition was \$8.5 t^{-1}. When no-till was considered, the reduction in sediment yield due to vegetative filter strips was from 2.2 to 1.6 t ac^{-1} $year^{-1}$ (26% reduction), and the cost of sediment reduction was \$11.8 t^{-1}. For a simplified analysis based on Iowa conditions, the cost per ton of sediment reduction ranged from \$1.4 t^{-1} to \$16.9 t^{-1}, the cost per pound of total nitrogen reduction ranged from \$0.4 lb^{-1} to \$2.3 lb^{-1}, and the cost per pound of total phosphorus reduction ranged from \$1.0 lb^{-1} to \$7.3 lb^{-1} (table 4-1).

Extent of area with potential benefit: A large percentage of crop land would benefit from the use of buffers. However, buffers would not be expected to have a direct impact on water quality where there is little runoff and resulting pollutant movement and/or where the buffer would not intercept shallow groundwater. One area in which the water quality benefits may be reduced is in areas where there is significant subsurface drainage such that subsurface flow is short-circuited through the drain lines so that there is minimal interaction with the buffer zone. Some of these areas may also have backslopes on drainage ditches that would likely minimize overland flow through the buffer. Care should be taken to design buffer systems in these locations such that the interaction of surface and ground water with the buffer system is maximized. For example, this may include placing buffers around surface intakes to the subsurface drainage system.

Limitations of adoption: The constraints associated with establishing buffer systems are mainly be associated with the cost of establishing the buffer and the cost to the producer of taking the land out of production. The risks of establishing buffers are that the water quality benefits may be reduced if the buffers are not designed to account for site conditions (i.e., topographic conditions) that minimize the area of the buffer interacting with flow, or the site conditions (e.g., poor soil conditions) that minimize infiltration.

Effect on other resources: Buffers can be expected to have a positive effect on soil and wildlife resources. By converting a portion of cropland to perennial vegetation, we would expect a positive result on soil resources. In addition, the perennial vegetation would provide habitat for wildlife.

Additional research or information needed: There is a need to better understand the in-field performance of buffers, where buffer integrity may be comprised by lack of vegetation or by features that allow bypass flow to occur through the buffer. Such research would provide much needed information on the performance of this conservation practice under likely common field conditions where non-idealized flow may occur. This information would be important for estimating the overall impact of these systems on a watershed scale. There is also a need to evaluate the performance of designs that are specific for water quality improvement. In particular, irregularly shaped buffers that are designed to intercept water as it moves off the source area in a uniform manner should be studied. These may prove to have greater water quality benefits than uniform-width buffers. Finally, there is a need for additional cost:benefit analyses for watersheds to further evaluate the costs and benefits of establishing buffer systems on a watershed scale.

Summary

Buffers and grassed waterways are broadly accepted practices for reducing nutrient runoff from agricultural fields. When properly located, designed, and maintained, buffers may be expected to trap on the order of 50% of incoming sediment, somewhat less for sediment-bound nutrients, and much less for dissolved nutrients. This performance will vary depending on conditions of the buffer and flow through the buffer, and the trapping may be greater than this when flow is nearly uniformly distributed, as has been the case in many plot studies to this point.

The water quality impact will be much lower if the buffer is not properly located, designed, or maintained. In-field management that reduces runoff load and distributes flow evenly along the buffer is important to maximize the effectiveness of the system.

Buffers are cost-effective when considering the water quality benefits. Analysis of the 2 million mile goal indicates a benefit:cost ratio of 4.1; for a 4 million mile goal, the benefit:cost ratio is 4.3.

The accuracy of impact assessments remains limited by lack of research data on watershed-scale effects of buffers and grassed waterways.

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