BUFFERS AND VEGETATIVE FILTER STRIPS

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Interpretive Summary

Practice definition

Buffers and filter strips are areas of permanent vegetation located within and between agricultural fields 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 they 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 will depend on the field, topographic, and climatic conditions at the site. In particular, these factors will impact loading to the buffer systems. So, areas with steeper slopes and less conservation practices in-field would be expected to result in greater loading to the buffer and 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) would also increase loading to the buffer system. However, there would be the expectation that they would still provide a water quality benefit even under more extreme conditions. Depending on site topography, surface water may concentrate prior to being intercepted by buffer systems. This would be expected to reduce buffer performance. In designing buffer systems potential concentration of surface water runoff should be considered and to the extent possible this occurrence should be mitigated through flow redistribution or 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.

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). Also, these narrow strips could 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 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 percent, with mean nitrate-removal efficiencies ranging from 48 to 85 percent in shallow groundwater under re-established riparian buffers (Simpkins et al. 200X).

Cost of practice implementation

The costs associated with buffer practices are from land being taken out of production and costs associated with planting, establishing, and maintaining the buffers. The costs will vary with location since land values would vary. Qiu (2003) studied the cost-effectiveness of installing buffers on two-small watersheds in Missouri considering a 10-yr evaluation horizon. They considered the private costs to be associated with land opportunity cost and buffer installation cost. From this, the annualized cost of the buffer was $62.4/ac.

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 also are beneficial in reducing the export of soluble pollutants. So, buffers are expected to reduce concentrations of nitrogen, phosphorus, and sediment in surface water runoff. In addition, when the buffers root zone intercepts shallow groundwater, buffers have been shown to reduce nitrate-nitrogen concentrations. The ranges in water quality improvement have been found to vary significantly but when buffers are designed and maintained appropriately 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 be commonly greater than 50%. However, the percent of groundwater interacting with the root zone of the buffer could be small.

In designing the buffer systems, the flow of either surface water or groundwater through 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 and best management practices implemented since buffers best serve as polishers of water moving through them.

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 vegetative filter strips reduced sediment yield from 4.5 t ac^{-1} yr^{-1} to 3.7 t ac^{-1} yr^{-1} (18% reduction). The approximate cost of sediment reduction for this tillage condition was \$9 t^{-1}. When no-till was considered the reduction in sediment yield due to vegetative filter strips was from 2.2 t ac^{-1} yr^{-1} to 1.6 t ac^{-1} yr^{-1} (26% reduction) and the cost of sediment reduction was \$11.8 t^{-1}. For a simplified analysis for Iowa conditions the cost per ton of sediment reduction ranged from \$1.4 t^{-1} to \$16.9 t^{-1}, cost per pound of total nitrogen reduction ranged from \$0.4 lb^{-1} to \$2.3 lb^{-1}, and cost per pound of total phosphorus reduction ranged from \$1.0 lb^{-1} to \$7.3 lb^{-1} (Table 1).

Extent of area with potential benefit

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/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 which likely minimizes 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. This may, for example, include placing buffers around surface intakes to the subsurface drainage system.

Limitations of Adoption

The constraints associated with establishing buffer systems would mainly be associated with the cost to establish the buffers and the cost to the producer of the land out of production. The risks of establishing buffers would be that if they are not designed to account for site conditions (i.e. topographic conditions) that minimize the area of buffer interacting with flow the water quality benefits may be reduced.

Effect on other resources

Buffers would 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 be expected to 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 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 a need to evaluate the performance of designs that are specific for water quality improvement. In particular, irregular shaped buffers that are designed to intercept water as it moves off the source area should be studied. These may prove to have greater water quality benefits than just a uniform width buffer. There is a need for additional cost:benefit analyses for watersheds in the Midwest to further evaluate the costs and benefits of establishing buffer systems on a watershed scale.

Buffer Practices

This paper describes the use of buffers/vegetative filter strips relative to water quality. In particular we are primarily discussing 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)

Common purposes of these herbaceous components would be 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;
- to reduce reduce sheet and rill erosion;
- to convey runoff from terraces, diversions, or other water concentrations without causing erosion or flooding; (Grassed Waterway)
- to reduce gully erosion. (Grassed Waterway and Vegetative Barrier)

A primary mechanism by which buffers provide water-quality benefits is through reducing flow velocities because the vegetation provides greater resistance to water flow. The reduction in overland flow velocity then causes deposition of some of the suspended particulates. Increased resistance to overland 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 would also occur in the buffer reducing the 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 due to dense, perennial vegetation providing greater resistance to erosion.

Flow conditions will 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. As a result, the flow rate entering buffer systems 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 effect whether the vegetation is submerged or unsubmerged. Conditions under which vegetation becomes submerged will 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. From this, the specific flow rate range for filter strip type systems would be less than approximately 0.22 ft^2 s^{-1} and the range for grassed waterways would be 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 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 efficiency from 9% to 100% (Arora et al. (1996), Arora et al. (1993), 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. (1994), Parsons et al. (1990), Patty et al. (1997), Schmitt et al. (1999), and Tingle et al. (1998)).

Numerous studies have also examined the nutrient-trapping effectiveness of buffers. Dosskey (2001) summarizes 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; and 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. (1996), Arora et al. (1993), 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. (1994), Parsons et al. (1990), 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; and 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 9-98% (Arora et al., 1996 and 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 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, a few studies have investigated the 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 60-90%, runoff loads by 50-80%, and total phosphorus loads by 50%. The retention of soluble phosphorus was about 20%. The retention of ammonium-nitrogen was 20-50%, 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 runoff reduction in the grass buffer averaged 56-72%, 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. (2005) 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; and Helmers et al., 2002). In some cases, narrow buffers have been shown to provide significant benefits. Narrow buffers (<3 ft.) such as vegetative barriers have been shown to trap significant amounts of sediment (Van Dilk et al., 1996 and 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 with out grass hedges. These systems would be narrow grass hedges planted on the contour along a hillslope. These hedges would normally use stiff-stemmed grasses to reduce overland flow velocity and promote sediment deposition. These 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 would be applicable over a wider range of flow conditions than a buffer that is intended to intercept shallow overland flow since these are designed to control concentrated flow erosion. So, while drainage area into the buffer is important, the performance of narrow grass hedges highlights that a continuous well maintained buffer edge may just as important for maximizing 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, it would likely be expected that nutrients strongly bound to sediment such as phosphorus would have reductions lower but similar to sediment reductions, but dissolved nutrients would have lower reductions and their reduction would be closely tied to infiltration. Relative to nutrient trapping buffers would likely be less effective than for sediment. Daniels and Gilliam (1996) note 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 are 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 they 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 that 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 41-99% for the gross area. Helmers et al. (2005b) found through modeling sediment trapping in a buffer 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 adversely effect 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 could be to use vegetative barriers on the upslope edge of buffers to distribute flow. Another approach may be to place vegetative barriers on the contour within field to minimize the occurrence or magnitude of concentrated flow.

The discussion above has concentrated on conditions where buffers are designed to function without submergence of the vegetation. In contrast, grassed waterways are designed to function under submerged vegetative conditions. Although grassed waterways have been widely used as part of conservation systems, only a 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 1970 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 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 the allowable velocity can be increased and vegetating the waterway is one form of protection (Haan et al., 1994). In many areas, reducing ephemeral gully erosion could have a significant impact on water quality. USDA (1996) reports that based on recent studies in 19 states, ephemeral gully erosion as a percentage of sheet and rill erosion ranged from 21% to 275%. So, being able to reduce this 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 comes from naturally occurring riparian forests. Denitrification has been measured in riparian and swamp forests in at least 18 different studies mostly in temperate region. 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} yr^{-1} are not uncommon for these studies but very low rates in the 0.89-4.5 lb N ac^{-1} yr^{-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. N removal through vegetation assimilation is clearly important (Lowrance et al., 1984) but requires active management of vegetation to maintain assimilation rates.

The capacity of vegetative 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 percent, with mean nitrate-removal efficiencies ranging from 48 to 85 percent in shallow groundwater under re-established riparian buffers (Simpkins et al., 200X). 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., 200X). 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 groundwater quality impacts of future buffers in the watershed.

Factors

Buffer Design Factors

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-analyses techniques for development of best-management-practice placement strategies by 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 timeline will be dependent on how quickly a dense stand of vegetation can be established. There could much grass growth in a single growing season. However to ensure long-term performance of the system it is important to not only establish a vigorous and dense stand of vegetation but to maintain the vegetative stand. So integrity of the buffer system is likely more important than age in evaluating the effectiveness of the system. So, some of the benefits could be observed in what may be considered a relatively short time frame.

Site Factors

Research has shown buffers to provide water quality benefits but that there is a significant range in the performance of the systems. This performance will depend 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 on the in-field performance of these systems. While it is expected that there would still be significant water quality benefits under these field conditions it is likely that the performance would be reduced compared to the results from the 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 a 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 would be to ensure buffer edges with dense vegetation that can tend 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 the 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 through direct 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, and 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 would 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. Also, they found that as the storm size increased the performance of the buffer from a sediment trapping efficiency perspective 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, this system would need to be designed to effectively convey water off the landscape while minimizing channel instability so the hydrology of the site and the soils in particular 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 is also some runoff reduction and direct water quality benefits of the grassed waterway. The reduction in runoff will likely be greater under smaller storm and runoff conditions when the specific flow rate in the grassed waterway is the range commonly expected in other buffer systems. Under larger precipitation events the grassed waterway will likely function just 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 there have been only a few studies that 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 does show 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, though. 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 there is a direct environmental benefit through the reduction in gully erosion with the use of grassed waterways provided the waterway is maintained so there is not short-circuiting of flow along the edge of the grassed waterway.

Another area that may be in need of future studies is to quantify what percent of shallow groundwater moving to a particular stream interacts with the buffer zone. One specific landscape in which this might be important is where there is an extensive subsurface tile drainage system that would short-circuit 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 greatly reduced and this 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 prevents overland flow from uniformly entering the stream. Rather the overland flow may flow to a low area and then enters the drainage way 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

The costs associated with buffer practices are through land being taken out of production. In some instances this could be productive farmland. As such, there is some negative attitude toward installation of these systems. However, there is not expected to be a yield reduction in the remainder of the agricultural land. 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 10-yr evaluation horizon. They considered the private costs to be associated with land opportunity cost and buffer installation cost. From this, the annualized cost of the buffer was $62.4/ac and the annualized benefit to be $73.30 where the annualized benefit 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 vegetative filter strips reduced sediment yield from 4.5 t ac^{-1} yr^{-1} to 3.7 t ac^{-1} yr^{-1} (18% reduction). The approximate cost of sediment reduction for this tillage condition was \$9 t^{-1}. When no-till was considered the reduction in sediment yield due to vegetative filter strips was from 2.2 t ac^{-1} yr^{-1} to 1.6 t ac^{-1} yr^{-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 Czapar et al. (2005) 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 1. This is a simplified analysis since the cost associated with the practice is just the land rental rate which was about \$135/acre in Iowa in 2005 (ISU Extension, 2005). There would be some other costs 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 science may be able to help provide a basis for such "green" payments.

The National Conservation Buffer Initiative had a goal of two million miles installed on private land by 2002. Santhi et al. (2001) studied the economic and environmental benefits of this goal and doubling this goal. This analysis likely did not consider the overall impacts of concentrated flow on the performance of buffer systems. However, their national estimated reduction in sediment loss, total nitrogen loss, and total phosphorus loss was 15.6%, 10.8%, and 11.7%, respectively, when considering the 2 million mile goal. When the goal was doubled to 4 million miles the national estimated reduction in sediment loss, total nitrogen loss, and total phosphorus loss was 28.9%, 27.2%, and 25.3%, respectively. While there are significant assumptions in developing these values, this gives an order of magnitude impact buffer systems might have if 2 million miles or 4 million miles of buffers were installed.

Santhi et al. (2001) evaluated the estimated annual economic impacts of implementing the National Conservation Buffer Initiative goal of 2 million miles as well as doubling this to 4 million miles. Their total net cost of the buffers considered the U.S. consumers loss from reduced supply, program payments to landowners, federal technical assistance cost, and the 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, they estimated that the annual net cost of the 2 million mile buffer goal was \$793 million and the value of water quality improvements was \$3288 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 \$1302 million and the return from water quality improvements was estimated to be \$5650 million for a benefit cost ratio of 4.3. They concluded their analyses showed the buffer programs to be cost-effective.

Summary

1. Buffers and grassed waterways are broadly accepted practices for reducing nutrient runoff from agricultural fields.

2. 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.

3. Impact will be much lower if not properly located designed, or maintained. In-field management that reduces runoff load and distributes it evenly along a buffer is important to maximize the effectiveness of the systems.

4. Buffers are cost effective. Analysis of the 2 million mile goal indicates a benefit:cost ratio of 4.1; a 4 million mile goal is 4.3.

5. 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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Table 1. Cost estimates per unit of reduction in sediment, nitrogen, and phosphorus.

Sediment

Treatment System	Soil Loss (t ac^{-1} yr^{-1})*	Percent Reduction Range Low	Percent Reduction Range High	Range of Pollutant Trapping Low (t ac^{-1} yr^{-1})	Range of Pollutant Trapping High (t ac^{-1} yr^{-1})	Annual operating cost (\$ ac^{-1}) **	Cost per ton reduction Low (\$ t^{-1})	Cost per ton reduction High (\$ t^{-1})
Typical Tillage	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

Treatment System	Nitrogen Loss (lb ac^{-1} yr^{-1})*	Percent Reduction Range Low	Percent Reduction Range High	Range of Pollutant Trapping Low (lb ac^{-1} yr^{-1})	Range of Pollutant Trapping High (lb ac^{-1} yr^{-1})	Annual operating cost (\$ ac^{-1}) **	Cost per lb reduction Low (\$ lb^{-1})	Cost per lb reduction High (\$ lb^{-1})
Typical Tillage	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

Treatment System	Phosphorus Loss (lb ac^{-1} yr^{-1})*	Percent Reduction Range Low	Percent Reduction Range High	Range of Pollutant Trapping Low (lb ac^{-1} yr^{-1})	Range of Pollutant Trapping High (lb ac^{-1} yr^{-1})	Annual operating cost (\$ ac^{-1}) **	Cost per lb reduction Low (\$ lb^{-1})	Cost per lb reduction High (\$ lb^{-1})
Typical Tillage	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

* Loss estimates from Czapar et al., 2005

** Assumes 5% of land area in buffer (cost is average land rental rate, $135/acre)