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# REDUCING SEDIMENTATION OF DEPRESSIONAL WETLANDS IN AGRICULTURAL LANDSCAPES

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*Abstract:* Depressional wetlands in agricultural landscapes are easily degraded by sediments and contaminants accumulated from their watersheds. Several best management practices can reduce transport of sediments into wetlands, including the establishment of vegetative buffers. We summarize the sources, transport dynamics, and effect of sediments, nutrients, and contaminants that threaten wetlands and the current knowledge of design and usefulness of grass buffers for protecting isolated wetlands. Buffer effectiveness is dependent on several factors, including vegetation structure, buffer width, attributes of the surrounding watershed (i.e., area, vegetative cover, slope and topography, soil type and structure, soil moisture, amount of herbicides and pesticides applied), and intensity and duration of rain events. To reduce dissolved contaminants from runoff, the water must infiltrate the soil where microbes or other processes can break down or sequester contaminants. But increasing infiltration also diminishes total water volume entering a wetland, which presents threats to wetland hydrology in semi-arid regions. Buffer effectiveness may be enhanced significantly by implementing other best management practices (e.g., conservation tillage, balancing input with nutrient requirements for livestock and crops, precision application of chemicals) in the surrounding watershed to diminish soil erosion and associated contaminant runoff. Buffers require regular maintenance to remove sediment build-up and replace damaged or over-mature vegetation. Further research is needed to establish guidelines for effective buffer width and structure, and such efforts should entail a coordinated, regional, multi-scale, multidisciplinary approach to evaluate buffer effectiveness and impacts. Direct measures in ''real-world'' systems and field validations of buffer-effectiveness models are crucial next steps in evaluating how grass buffers will impact the abiotic and biotic variables attributes that characterize small, isolated wetlands.

*Key Words:* contaminants, grass buffer, herbaceous buffer, infiltration, playa

## INTRODUCTION

Geographically isolated wetlands, or depressional wetlands surrounded by a defined surrounding upland watershed, constitute a significant proportion (46%–100%) of the wetland resource in arid, semi-arid, and subhumid regions of North America (Tiner 2003). Many depressional wetlands, such as prairie potholes and playas, occur in a context of cultivated croplands and grazed grasslands where erodible terrestrial soils accumulate in wetlands. Because most depressional wetlands represent the terminus of closed watersheds, they are subject to potentially large, rapid influxes of runoff and runoff-borne materials (e.g., sediments, chemicals). Wetlands in cultivated watersheds may contain 8.5 times more sediment than wetlands surrounded by grazed grasslands (Luo et al. 1997). One management practice designed to intercept sediments and contaminants washing into wetlands from precipitation and runoff is to buffer wetlands by establishing herbaceous (i.e., both grasses and forbs; hereafter ''grass'') strips (buffers or vegetative filter strips) around them (Haukos 1994, 1995). Specific recommendations for buffer structure, including width, species composition, and vegetation density, and information on the effectiveness of buffers are currently being sought by wetland managers interested in applying this technique.

An overall protection strategy for wetlands requires a basic understanding of the processes that affect not only wetlands, but also the buffers themselves (Mitchell 2002). Our objectives here are to synthesize existing scientific information on the use of grass buffers for wetlands in agricultural landscapes, identify remaining knowledge gaps, and provide recommendations for the type and configuration of grass buffers that should be tested experimentally. We first summarize the sources, transport dynamics, and effects of sediments and contaminants that threaten wetlands, especially those that may be mitigated by buffers and other best management practices (BMP). This background provides a basic framework for assessing buffer need, design, and potential effectiveness. We then synthesize the current knowledge about general buffer design and maintenance, as well as other BMPs that may greatly increase the effectiveness of buffers for small, isolated wetlands. Finally, we outline the research needs for improving our understanding of buffer effectiveness. For many examples, we draw from literature on the semi-arid High Plains (HP) region of the United States that includes ~25,000–60,000 playa wetlands in portions of Texas, New Mexico, Oklahoma, Kansas, Colorado, Nebraska, Wyoming, and Montana (Smith 2003).

We conducted extensive searches of existing literature in databases such as Agricola, Cambridge Scientific Abstracts (including agricultural, biological, ecological, environmental, pollution, and engineering topical areas), Water Resources Abstracts, Wildlife Worldwide (NISC), First Search, Web of Science (Science Citation Index), Dissertation Abstracts, and others. Search terms we used included (but were not limited to) buffer, wetland buffer, filter strip, vegetated filter strip (VFS), isolated wetland, playa, playa wetland, and wetland protection. We also checked publications cited in existing previously published reviews of, and bibliographies for, buffers and similar structures, as well as the literature cited sections of publications that we reviewed. In addition to literature searches, we conducted keyword searches in library catalogues (U.S. Geological Survey's library system, Colorado State University's Morgan Library, and Colorado Prospector libraries) to locate and access potentially important publications not available locally. We also searched the World Wide Web (via Google Scholar and other search engines) for helpful websites, including that of the Natural Resources Conservation Service (NRCS), and interviewed wetland, soil, wildlife, and agricultural scientists, natural resource managers, and other experts on topics relevant to buffers and wetlands.

## SEDIMENTS AND CONTAMINANTS: TRANSPORT AND THREATS TO WETLANDS

### Sediments

Sedimentation is one of the greatest known runoff-associated threats to wetlands in arid, semi-arid, and subhumid regions. In the Southern High Plains (SHP) region of Texas and New Mexico, sedimentation rates of wetlands within cultivated agricultural lands average 4.8 and 9.7 mm $yr^{-1}$ for fine- and medium-grained soil, respectively, reflecting during the first 60 years of cultivation history; at these rates, cropland playas would totally fill with sediments within 95 years (Luo et al. 1997). In South Dakota, vertical accretion rates of inorganic sediments (clay, silt, and sand) in wetlands within cultivated landscapes average 4–6 mm $yr^{-1}$ (Martin and Hartman 1987). At current rates of sedimentation, losses of 57% of cultivated wetlands in the Prairie Pothole Region are projected within 200 years (Gleason 2001). Further, sediment burial depths as small as 5 mm can cause marked reductions in seedling (~92%) and invertebrate emergence (~100%; Gleason et al. 2003).

Watershed-scale factors that affect rates of erosion and sedimentation include size, slope, soil texture, and land use. Typically, erosion occurs at faster rates where slopes are greater, soils are coarse or sandier, and/or row-cropping is the dominant land use than where slopes are minimal, soils are finer-grained with particles more firmly bound together, and/or grassland grazing is the dominant land use. Unmanaged grazing, however, can lead to significant soil erosion and sedimentation even in grassland watersheds (Luo et al. 1997, 1999). Rates of soil erosion are also influenced by the amount and intensity of runoff from precipitation, soil management, irrigation techniques, and crop attributes, such as amount of post-harvest residue, stem density, and percent cover of live vegetation (Sprague and Triplett 1986, Eghball et al. 2000). No-till methods in croplands usually provide greater protection from soil erosion than disking or other forms of tillage (e.g., Mickelson et al. 2001). Of crops common to the HP, wheat typically forms the greatest stem density and therefore is likely to provide better protection against erosion than other crop covers. Furthermore, wheat harvesting generally entails leaving up to 15 cm of stubble to protect soil from erosion and trap snow (moisture for the next growing season), whereas post-harvest residue in cotton fields is often disked or mulched into the soil (Sprague and Triplett 1996, Mickelson et al. 2001), leaving the fields relatively bare between growing seasons.

### Nutrients

Nitrogen (N) and phosphorus (P) entering wetlands is a significant problem throughout the world. Primary sources of excess nutrients include manures and synthetic fertilizers applied to surrounding agricultural lands. In localized areas, wetlands are heavily impacted by feedlot runoff and municipality or feedlot wastewater and sludges dumped directly into wetlands. Factors affecting the extent and rate of nutrient transport into wetlands include the intensity and duration of precipitation and irrigation runoff, temperature (i.e., frozen versus liquid precipitation), antecedent soil moisture, percent cover of residual vegetation, soil type, and slope.

Runoff from precipitation or irrigation easily transports both dissolved (water soluble) and undissolved (bound to sediment or debris) forms of N and P over terrestrial systems to wetlands (Magette et al. 1989). When N enters terrestrial systems, it may be fixed by soil bacteria, taken up by plants, or volatilized. If not intercepted, however, it may be transported into a wetland where it contributes to accumulations of ammonia in sediments (Mitsch and Gosselink 2000). Most excess P in agricultural systems is undissolved, bound to substrates, and may be transported if the substrates become mobilized. Thus, even though fine-textured soils are not as susceptible to erosion as coarser soils, runoff from fine-textured soils is likely to contain more undissolved P than that from coarse-textured soils because the greater particle density of fine soils provides more surface area to which P may bind (Abu-Zreig et al. 2003). Undissolved P is unavailable to plants even at relatively high concentrations (Miyasaka and Habte 2001); thus, it is likely to accumulate in croplands and, if the soils and plant residues to which the P is bound become mobilized, it likely will end up in a wetland where it can persist in the sediment for decades (Sharpley et al. 2001). Unlike undissolved P, dissolved P is easily transported in water (Sharpley et al. 2001); thus, even debris-free runoff can transport dissolved P into wetlands.

An overabundance of N and P in wetlands promotes excessive primary production, the end result of which is significant deposition of decomposed material and the associated anoxia (Sharpley et al. 2001). Within a wetland, algal blooms and eventual anoxia can significantly alter chemical and community composition of that wetland (Rocke and Samuel 1999, Mitsch and Gosselink 2000), which, in turn, could further alter the biotic community. Wetlands that are impacted by the level of nutrients associated with feedlots are characterized by significantly reduced biodiversity, particularly of invertebrates (Irwin et al. 1996).

### Pesticides and Heavy Metals

Pesticides and heavy metals are also easily transported into wetlands via runoff. Furthermore, aerial applications of pesticides generally drift beyond their target zones, and many pesticides can travel long distances on soil particles carried by wind or in rainfall. In the SHP region, herbicides have been detected in nearly all playas tested, even in watersheds considered relatively undisturbed (Irwin et al. 1996, Thurman et al. 2000). Although the impacts of herbicides on living organisms still requires significant research, there is mounting evidence that their effects may be long-term and have profound implications for wildlife populations. For example, Hayes et al. (2002) suspect that herbicides are causing demasculinization among male frogs. Relyea et al. (2005) found that Roundup, one of the most widely used herbicides on croplands today, reduced tadpole survival and biomass by 40% at experimental concentrations of 1.3 mg AI/L; the surfactant (polyethoxylated tallowamine) used in Roundup is suspected of damaging the animals' respiratory surfaces (Relyea et al. 2005). Especially compelling about the Relyea et al. (2005) study was that concentrations of Roundup used in the study were three times less than the concentrations expected in agricultural landscapes where Roundup is used.

Of heavy metals or metalloids known to harm wildlife, arsenic is among the most-widely distributed, possibly because it can be transported via wind-borne soil particles (Irwin et al. 1996). Arsenic is well-known to have deleterious effects on wildlife, especially fetuses and growing young (Eisler 1988). Copper also occurs at relatively high levels in wetlands, due, in part, to feedlot runoff (i.e., excessive dietary intake and subsequent excretion) and runoff from copper-based pesticides. Copper can be transported into wetlands and accumulate to levels that are toxic to aquatic plants and animals (Wu et al. 2003). Boron, chromium, iron, manganese, selenium, vanadium, and zinc are also of concern in many wetlands, although these sources of contamination tend to be relatively localized, and significant sources of most of these elements are petroleum-extraction activities, urban sewage, and feedlots.

## OVERLAND WATER FLOW VERSUS SOIL INFILTRATION

Because water is the primary agent responsible for mobilizing sediments and contaminants in most watersheds, the primary means of keeping mobilized sediments and contaminants out of wetlands are to reduce the velocity of overland water flows (runoff) and to increase soil infiltration of contaminated water. However, slowing runoff velocity and promoting infiltration could result in diminished flows of water into wetlands. For example, van der Kamp et al. (1999) found that small, isolated wetlands in central Saskatchewan completely dried out after one-third of their watershed had been converted from unirrigated cropland to a perennial, unmanaged cover of smooth brome (*Bromus inermis* Leyss.) and alfalfa (*Medicago sativa* L.). Increased infiltration and high water demands of smooth brome likely contributed to the dewatering of these wetlands. To date, there has been little research to evaluate the ways in which buffers affect the hydrologies of their associated wetlands (but see van der Kamp et al. 1999 and Abu-Zreig et al. 2004), an issue of significant concern in arid and semi-arid regions.

Runoff velocity is largely a factor of runoff volume, slope, surface roughness, and obstructive factors on the slope. Methods of reducing runoff velocity via semipermeable obstructions include no-till soil preparation (vegetative residue serves as a filter), tilling crop rows along landscape contours instead of parallel with the slope (the furrows serve as tiny 'check dams'), and planting buffers. As runoff velocity diminishes, solids—including sediments, plant residues, and undissolved contaminants—begin to settle out of the water. Heavier and larger particles of soil (e.g., gravel and sand) and vegetative residue drop out first, and as velocity diminishes and ponding time increases, silt particles will settle (Wilson 1967). Clay particles are among the last to settle, and even after runoff has filtered through a wide buffer, it may still contain clay particles (Van Dijk et al. 1996).

Infiltration rates are affected by many climatic, biotic, and abiotic factors, including 1) rainfall duration and intensity (long, gentle rainfalls usually result in more infiltration than short, intense rainfall events); 2) antecedent soil-moisture conditions (infiltration is greater in dry than saturated soils [Lin et al. 1998]); 3) soil structure and texture (infiltration rates tend to be greater in more-porous, coarse-textured soils than in finer, tighter soils [Lin et al. 1998]); 4) slope and evenness of surface flow (more infiltration occurs with even surface flows on gentle slopes than with uneven flows on steep slopes); 5) stem density (denser stands of vegetation retain more runoff than thinner stands [Kemper et al. 1992; Eghball et al. 2000]); and 6) grass structure and growth form. Moreover, Van Dijk et al. (1996) found that, for a given buffer width, older grass retained more water than younger grass, due primarily to roughness coefficients that increased with increasing stem density and litter residue typical in stands of older grasses.

## PROPOSED SOLUTIONS: BEST MANAGEMENT PRACTICES

### Establishing Herbaceous Buffers to Protect Wetlands from Sediments and Contaminants

Fully functional, strategically located, and well-designed buffers can slow the velocity of runoff enough to allow most sediments and plant residues to settle out before reaching a wetland. Buffers also may be designed to promote soil infiltration of contaminated runoff; once contaminants enter the soil, plant uptake or microbial action and other decay processes can sequester and neutralize dissolved contaminants. For example, Seybold et al. (2001) found that 53%–73% of the herbicides atrazine and metolachlor contained in runoff on clay loam soil was removed by VFSs, primarily due to soil adsorption and infiltration of dissolved herbicides. A number of factors, however, can contribute to buffer failure, including directed flows of runoff that uproot or overtop buffer vegetation and burial of buffer vegetation due to buildups of sediments. Buffers alone may not be adequate for reducing the transport of contaminants into wetlands, and they should be regarded as part of an overall Best Management Practice (BMP) strategy designed to reduce input and rates of sediment, nutrient, and contaminant transport in a watershed.

### Reducing Soil Erosion and Sedimentation

Reductions in soil erosion and sedimentation can be accomplished by several means (Table 1). Changes in farming and irrigation practices, such as conversion from irrigation to dryland farming and conversion from flood irrigation (with the concomitant return of tailwater into wetlands) to center-pivot irrigation can reduce erosion of cropland soils. Common BMPs for managing water- and wind-driven soil erosion include conservation tillage (minimal or no tillage), contour tilling, terracing, establishing Conservation Reserve Program (CRP) plantings in previously cultivated land, and vegetative buffers. Although buffers are a potentially important line of defense for protecting watersheds, they alone may not be enough. In many circumstances, a combination of BMPs are necessary to sufficiently reduce sedimentation in wetlands.

Table 1. Methods for reducing input of sediments, nutrients, and contaminants to depressional wetlands in agricultural systems.

| **Soil erosion and sedimentation** | |
|---|---|
| Convert from irrigation to dryland farming | Luckey et al. 1988 |
| Convert from flood to center-pivot irrigation | Luckey et al. 1988 |
| Conservation tillage (minimum or no tillage) | Sprague and Triplett 1986, Bunn 1997 |
| Contour tilling and terracing | Luo et al. 1999, Mickelson et al. 2001, Sharpley et al. 2001 |
| Establish Conservation Reserve Program plantings | Allen and Vandever 2005 |
| Establish vegetative barrier (buffer) | Van Dijk et al. 1996, citations in Melcher and Skagen 2005a,b |
| **Nutrients** | |
| Minimize nutrient input | Sharpley et al. 2001 |
| Fine-tune fertilizer applications | Sharpley et al. 2001 |
| Refine dietary intake of livestock | Sharpley et al. 2001 |
| Prevent feedlot runoff | Sharpley et al. 2001 |
| Manage application of nutrients | Sharpley et al. 2001 |
| Delay application when runoff is expected | Sharpley et al. 2001 |
| Establish a no-application zone around wetlands | Sharpley et al. 2001 |
| Apply nitrogen to soil surface | King 1981 |
| Conservation tillage | Sprague and Triplett 1986, Baker et al. 1995 |
| Establish vegetative barrier (buffer) | Sharpley et al. 2001, citations in Melcher and Skagen 2005a,b |
| **Herbicides and other contaminants** | |
| Establish no-spray zones around wetlands and buffers | Flickinger et al. (1991) |
| Avoid spraying during rain or windy conditions | Irwin et al. 1996, Patty et al. 1997, Tingle et al. 1998, Hayes et al. 2002 |
| Conservation tillage and contour tilling | Baker et al. 1995, Hoffman et al. 1995 |
| Increase soil porosity by mulching or disking | Mickelson et al. 2001 |
| Establish vegetative barrier (buffer) | Van Dijk et al. 1996, citations in Melcher and Skagen 2005a,b |

### Reducing Nutrient Input and Transport

BMPs for managing nutrients include reducing input, altering application methods, and precluding the mobility of soils and runoff (Sharpley et al. 2001). To meet the N requirements of crops, many farmers apply manure to croplands, but adequate inputs of N can result in excessive inputs of P because of the typical N:P ratios in most manures. Also, livestock producers often provide their animals with more nutrients than needed, including metallic elements (e.g., copper), which are subsequently excreted. Thus, reducing nutrient input within a watershed requires not only fine-tuning fertilizer applications, but also refining the dietary intake of livestock and preventing feedlot runoff. Other input-based BMPs include delaying applications of nutrient-rich manures or fertilizers within a watershed when intense, prolonged rain or other significant water runoff is likely to occur in the immediate future. Perhaps one of the most feasible BMPs for reducing nutrient input is to establish a no-application zone around wetlands. Local groups of farmers and ranchers also may be encouraged to establish manure banks for transporting manures from P-rich operations to operations deficient in P (Sharpley et al. 2001).

Combining methods of nutrient application and soil preparation may affect uptake by plants and the eventual transport of nutrients. For example, grass uptake of N is greater when N is surface-applied rather than disked into the soil (King 1981). Concomitant conservation tillage would help reduce overland transport of any remaining N by reducing erosion of sediments and plant residues to which undissolved nutrients are bound (Sprague and Triplett 1986). Minimizing nutrient input, however, should always remain a first-line defense against the leaching of excess nutrients into wetlands. For example, even where vegetation cover or surface roughness preclude surface runoff of undissolved nutrients, dissolved P and N may still flow through subsurface strata. Although significant amounts of dissolved P may be bound up through fixation with subsoils deficient in P, some conditions can retard fixation or result in P bypassing this process altogether (Sharpley et al. 2001); this is the case with typical soils in the HP (low pH, low percent organic matter, sandy texture, and significant soil porosity). The dissolved nutrients then may leach through subsurface strata and eventually enter nearby wetlands. Once nutrient levels are beyond the capacities of animals, plants, and soils to use or adsorb them, they are at risk of becoming mobilized and entering wetlands. In such cases, vegetative barriers that help reduce runoff velocity, amount, and contaminants are needed to protect wetlands.

### Reducing Input and Transport of Herbicides and Other Contaminants

Depending on local conditions, BMPs that minimize nutrient input and transport also may reduce the amount of herbicides, insecticides, and heavy metals that enter wetlands. The amount and types of pesticides used should be carefully weighed against the long-term consequences of using them. In many cases, there may be less-toxic, but equally effective, alternatives. BMPs to reduce both aerial and terrestrial transport of pesticides include establishing no-spray zones around wetlands and buffers and delaying application when precipitation or strong winds are likely or predicted. For example, Patty et al. (1997) found an inverse relationship between the amount of herbicide residues in runoff and the time elapsing between herbicide application and subsequent rainfall.

Typically, reducing adsorbed herbicides (i.e., bound to sediments) in precipitation or irrigation runoff requires that the sediments be allowed to settle, and reducing dissolved herbicides requires that runoff be allowed to infiltrate the soil (Dillaha et al. 1986, Arora et al. 1996, Misra et al. 1996, Patty et al. 1997, Tingle et al. 1998, Seybold et al. 2001). Baker et al. (1995) found that conservation tillage alone reduced the runoff of herbicides by an average of 60% simply by diminishing soil erosion (i.e., the transport of adsorbed herbicides). Overall, however, the ways in which different tillage practices affect the concentrations of herbicides in runoff depends on the duration/intensity of rainfall, time elapsed between application and rainfall (or irrigation), residual herbicides remaining on soil and plant surfaces prior to application, adsorption capabilities of herbicides, and the amount of area treated. Because infiltration tends to be greater when soil porosity is greater, mulching or disking after heavy or frequent herbicide applications may be helpful, although this risks increasing soil erosion and may be more practical where soil erosion is not especially problematic. When other BMPs are not adequate, establishing grass buffers will help to protect wetlands.

## DESIGN AND EFFECTIVENESS OF HERBACEOUS BUFFERS

Several terms are used in reference to buffers composed of grass (or grasses and forbs); general terms include grass buffer or grass filter, and specific terms include vegetated filter strip (VFS), grass hedge, and grassed waterway, each of which performs a similar function but with a slightly different design, placement, or purpose (U.S. Department of Agriculture 2000). Generally, a grass buffer is established around the perimeter of a wetland downslope of a potential source of runoff. Buffers may be planted singly or in bands farther upslope to keep soils from being transported off croplands or to supplement or protect a primary wetland buffer downslope, and they may be established around the perimeters of feedlot lagoons or other contaminated wetlands to intercept flows of contaminants and nutrients contained in overflows. Generally, VFSs are established singly around the perimeters of wetlands downslope of a runoff source, and grass hedges are planted in repeated bands along slope contours to hold soils in place on steeper slopes and/or where wind erosion is significant (Van Dijk et al. 1996).

### Buffer Design Considerations

Variable ecological conditions strongly affect the design and effectiveness of buffers, yet most published works on herbaceous buffers involve short-term studies in highly controlled field plots or trays (with simulated slopes) that were subjected to simulated rainfall applied in even sheet flows, primarily for preventing erosion and sedimentation (for a tabular summary of different study designs, variables, and results, see Appendix 2 in Melcher and Skagen 2005a). Of the ‘‘real-world’’ buffer studies that have been conducted, most involved woody or woody/herbaceous vegetation for protecting riparian or coastal systems in well-watered regions (e.g., the U.S. Mid-Atlantic, Upper Midwest, Southeast, and Pacific Northwest regions). Few studies have evaluated buffers explicitly for protecting isolated wetlands (but see Wilson 1967). Difficulties in determining the locations of wetland boundaries can make buffer placement problematic, especially in regions where dynamic hydrology results in the temporal movement of vegetative zones up and down in elevation (N. H. Euliss, U.S. Geological Survey, pers. comm.). In regions such as the prairie potholes, it may be pragmatic to place the inner boundary of a buffer at the maximum pool boundary of the wetland (N. H. Euliss, U.S. Geological Survey, pers. comm.).

Effective buffer widths reported in the literature range from < 1 m (generally for grass hedges; e.g., Kemper et al. 1992, Eghball et al. 2000) to 300 m (e.g., Wilson 1967, Wong and McCuen 1982). Generally, wider buffers are established where sediment loads, contaminant levels, and runoff flows are extreme, and/or where watersheds are large. Buffer size is also strongly affected by the availability of adjacent land and buffer maintenance that landowners are willing to dedicate to buffers. Castelle et al. (1994) provide a useful graphic that summarizes the range of buffer widths in the literature for addressing specific runoff problems: generally, reducing most sediments requires buffers of ~10–60 m, and buffers of 10–90 m are generally adequate for reducing nutrients (Castelle et al. 1994). Most research on grass buffers has entailed tall- or medium-height grasses, not native shortgrasses.

For a given buffer width, sediment-trapping efficiency (STE) increases nonlinearly with increasing soil-particle size (Wilson 1967, Wong and McCuen 1982, Dosskey et al. 1997, Abu-Zreig 2001). For example, if the desired amount of sediment removal on a 2% slope is increased from 90% to 95%, the buffer width must be doubled from 30.5 to 61 m (Wong and McCuen 1982). Van Dijk et al. (1996) report that most large particles drop out within the first 0.6 m of a grass VFS, but particles < 125 microns in size (i.e., clay particles) are able to pass through, regardless of strip width. In a southern Arizona watershed, maximum STE was achieved at 3.5 m for sand, 15.4 m for silt, and 91.5 m for clay particles (Wilson 1967). Width also depends on land-use, slope, and other factors. Because erosion is typically much greater in croplands than in grazed grasslands (Luo et al. 1997), buffers in croplands must be wider than those in grasslands.

Where nutrient runoff is significant (especially dissolved nutrients), or where concentrations of dissolved agrochemicals are high and likely to enter nearby wetlands, buffer widths and stem densities will need to be greater to promote runoff ponding and infiltration. Undissolved pollutants will settle with sediments to which they are bound. Thus, if buffer width is adequate for trapping most sediments, including clay particles that can adsorb more contaminants that coarser particles, it will be reasonably adequate for trapping most sediment-bound contaminants. Where feedlot runoff may be transported into a wetland, a single buffer may not be enough, and some authors suggest establishing bands of buffers to trap nutrients repeatedly as runoff travels downslope. However, the relationships between nutrient/herbicide reductions and filter width are complicated greatly by soil texture and porosity (i.e., adsorption and infiltration capacity), slope, the amount and intensity of rainfall (Schmitt et al. 1999), antecedent soil-moisture, and other factors. Also, previously undissolved nutrients trapped in buffers may eventually dissolve or mineralize and become mobilized again in future runoff. Thus, results of studies evaluating buffer effectiveness for removing pollutants are far more varied than those of sediment-trapping studies.

Buffer STE exhibits a nonlinear trend, with the greatest benefits imparted in the first few meters of buffer encountered by runoff (e.g., Wong and McCuen 1982, Abu-Zreig 2001). Buffer widths may reach a threshold beyond which their effectiveness does not increase. Buffers that are wider than necessary are likely to result in more infiltration (Detenbeck et al. 2002, Abu-Zreig et al. 2004) and can significantly affect wetland hydrological regimes. Where large, directed flows of runoff threaten the integrity of buffers, rather than increasing buffer width, managers can strategically locate buffers in the specific areas of a given watershed that are responsible for predictable and disproportionately large amounts of runoff, in effect, to 'buffer the buffer' from inundation (Qiu 2003).

Tillage method also significantly impacts effectiveness of a given buffer width. Conventional tillage generally requires wider buffers than conservation tillage, although the results of studies evaluating this relationship are equivocal due to variation in runoff problems being measured (e.g., sediments versus nutrients and other contaminants), crop type, percent crop residue and extent of mulching, soil type, rainfall intensity and duration, slope, and the ratio of dissolved to undissolved contaminants in the runoff (e.g., Sprague and Triplett 1986, Shaw and Webster 1994, Bunn 1997, Barfield et al. 1998, Tingle et al. 1998, Mickelson et al. 2001). One study revealed the inadequacy of 0.5- and 1-m VFSs buffering conventionally tilled cotton fields in southeastern U.S. (Murphy and Shaw 1997), consistent with studies that promote minimum buffer widths of 10–15 m for most sediment runoff scenarios.

Since 1994, the Partners for Wildlife Program of the U.S. Fish and Wildlife Services has promoted a buffer program for playas in the SHP, recommending a minimum average buffer width of ~33 m of a diversity of native shortgrasses, midgrasses, and mixed forbs. Where focused runoff occurs (channels, drainageways, abrupt changes in landscape contour), buffers may need to be as wide as 50–70 m, and where slopes exceed 4%, buffer widths should be widened according to the amount of land a landowner is willing to devote to buffers. The range of buffer widths recommended for playas (30–90 m) has been based on a 'best judgment' approach according to individual watershed conditions (Smith 2003).

Several characteristics are considered favorable for grasses potentially used in wetland buffers: native status, an ability to germinate in and tolerate the soil and climatic conditions, the ability to grow up through accumulating sediments, and local commercial availability of diverse, native seed mixes. Dillaha et al. (1986) recommends removal of woody material from grass VFS because it can disrupt the evenness of runoff flow through it, thus impairing the VFS's longevity and effectiveness. In general, nutrient uptake will require actively growing leafy plants.

### Balancing Overland Water Flow With Infiltration

By definition, buffers and other BMPs designed to promote infiltration also diminish overland water flow to wetlands. Several factors influence the volume of water that infiltrates the soil, including buffer width, surrounding vegetation and land-use, historical land-use, buffer maintenance, and other practices implemented. Perennial vegetation surrounding wetlands can diminish runoff by promoting infiltration. Less runoff enters wetlands in watersheds currently enrolled in the CRP than in currently cultivated watersheds (Detenbeck et al. 2002). The high water demand of various non-native grasses common within most CRP plantings, especially smooth brome, exacerbates dewatering of wetlands (N. H. Euliss, U.S. Geological Survey, pers. comm.). Tilling and disking generally promote infiltration, whereas soil compaction will diminish or even preclude infiltration. Because less runoff is able to penetrate undisturbed prairie soils than historically tilled soils of land under the CRP program, water levels in wetlands surrounded by native prairie are often higher than those surrounded by CRP uplands (Detenbeck et al. 2002).

Overall, when planning buffers, resource managers will have to consider and carefully balance infiltration with the amount of water that flows into a wetland (van der Kamp et al. 1999, Abu-Zreig et al. 2004). In some watersheds, runoff of dissolved contaminants may be high enough to warrant BMPs that promote significant infiltration. However, the probability that high levels of contaminated runoff will chronically (v. short-term) impact a given wetland should be factored in, if possible. Where high levels of dissolved contaminants may be temporary, the long-term effects of diminishing runoff to the wetland by promoting infiltration could be more damaging than short-term influxes of contaminants. To some extent, the half-life, persistence, and relative toxicity of the contaminants involved will also need consideration before implementing infiltration-promoting BMPs. Alternative approaches to buffering also should be considered when balancing infiltration with wetland hydrology. For example, grass hedges or very dense VFSs established only around and immediately downslope of feedlot perimeters may be useful for lightening the burdens of contaminants moving downslope while still allowing precipitation gathered from the rest of the watershed to reach the wetland.

### Models for Predicting or Evaluating Buffer Effectiveness

Currently, there are a number of models for predicting buffer effectiveness, most of which need rigorous model testing and validation with real-world data to reflect the broad array of ecological conditions under which buffers are implemented. Models developed to-date include CREAMS (Chemical Runoff and Erosion from Agricultural Management Systems; Knisel 1980), GLEAMS (Groundwater Loading Effects of Agricultural Management Systems; Leonard et al. 1987), REMM (Riparian Ecosystem Management Model; Inamdar et al. 2000), and VFSMOD (Vegetative Filter Strip Model; Abu-Zreig 2001). GLEAMS deals with ground-water pollution and may have useful application for determining water loss in buffers. REMM is a complicated model that incorporates evapotranspiration losses. Models that provide the level of sophistication likely needed to incorporate the suite of conditions affecting isolated wetland systems are not yet user-friendly. A review of models available prior to 1990 is available in Dillaha (1990).

### Buffer Maintenance

Constant monitoring of buffer integrity is necessary and some level of buffer maintenance may be required. However, little has been published on the effects and effectiveness of different buffer-maintenance regimes (Dillaha et al. 1989, Castelle et al. 1994, Dewald et al. 1996). Buffers can become overburdened with sediments or plant materials that have accumulated high levels of nutrients, rendering them ineffective. When breached by directed or relatively deep flows (Dillaha et al. 1986) or due to activities of fossorial animals (Kemper et al. 1992), buffers require immediate repair and reseeding. If sediment loads become too great for buffers to remain effective, they may need disking, grading, or excavation, followed by reseeding (Dosskey et al. 1997, Natural Resource Conservation Service 2005). Because runoff rarely occurs in even sheetflows across a buffer, certain patches may hold larger sediment loads, in which case only those patches may need maintenance. In such instances, further evaluation of management practices in the watershed may help to identify and remove practices promoting such sediment loads. Disturbance techniques such as disking or burning may be useful for promoting new growth and vigor in existing buffer grasses, restoring grasses after damage, eliminating invasive or exotic species, or preparing a seedbed for new grasses. Where nutrient runoff is excessive, nutrient accumulation via plant uptake may require removal through haying (mowing would leave the nutrients in place) or short-term grazing. Burning is a common and acceptable practice for vegetation management in the Texas SHP (Wright and Bailey 1982), although little is known about potentially short-term effects of burning buffer vegetation. Burning on a 3-year rotational basis, burning only a portion of the buffer (e.g., up to one-third) in any one year, seems a reasonable approach.

## CONCLUSIONS AND RECOMMENDATIONS

Best management practices, including vegetative buffers, are useful in addressing sedimentation and contamination problems that affect wetlands. Resource managers working closely with farmers and ranchers to develop a holistic program of BMPs—of which buffers are only a part—should implement BMPs before buffers are established, as non-buffer BMPs may dictate more precisely the buffer designs necessary for a given watershed. Part of any BMP program that incorporates buffers also must include buffer maintenance to promote their longevity and effectiveness.

We strongly encourage a collaborative, interdisciplinary approach to playa buffer research that integrates hydrology, soil science, zoology, botany, entomology, agricultural engineering, ecological modeling, geospatial mapping, and social science. To date, research on grass buffers has focused on their design and effectiveness in tightly controlled experimental situations, the results of which have provided a solid foundation from which to take the next major step: testing in "real-world" watersheds under the array of natural conditions to which buffers are subjected. We emphasize the need for comparable replicates and controls, adequate sample sizes, measures of effectiveness, and the collection of pre-and post-treatment data. Without these fundamental bases for comparison, it will be difficult to determine the real effects of buffers. Meeting the range of information needs pertaining to wetlands and buffers will require a coordinated, regional program conducted at several scales, from individual watersheds to a regional scale.

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