Appendix C

National Agroforestry Center (NAC)

Synthesis of Design Guidelines and Experimental Data for Water Quality Function in Agricultural Landscapes in the Intermountain West

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Photo credit: Susan Buffler

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Abstract

Currently, there is no scientific literature examining appropriate riparian buffer widths for water quality for streams on private agriculturally dominated lands in arid regions of the Intermountain West. The initial step in this research effort was a review of buffer research as documented in the literature in other physiographic regions of the United States. Research findings on appropriate buffer widths for water quality parameters were synthesized using a matrix format. Differences between arid and non-arid landscape characteristics, soil, topography, vegetation, climate and hydrology and their effect on buffers for water quality were also researched. The combined research findings in this document (Appendix C) were then used to develop Buffer Design Guidelines for Water Quality and Wildlife Habitat Functions on Agricultural Landcapes in the Intermountain West.

Preface

Water quality is a major global issue. It is estimated that over 1 billion people worldwide do not have access to safe, clean drinking water. Just 3% of all water on earth is fresh water but only 0.003% is usable (Leopold 1997; Mason 2002). Although many of the issues regarding water are political and economic, the importance of clean water for human, aquatic, and riparian health cannot be understated.

The Clean Water Act (CWA) of 1972 was passed by the U.S. Congress in response to increasing concerns about water pollution. The Clean Water Act's mission is to **"restore and maintain the chemical, physical, and biological integrity of the Nation's Waters"** (EPA 2005b). This statute uses a number of regulatory and non-regulatory tools to implement reduction of pollutants into waterbodies and provides for financing of water treatment facilities and management of polluted runoff.

Water quality, however, is a social value imposed by humans for some existing or potential beneficial use (Fry et al. 1994). The CWA directs states and tribes to protect water quality for specific beneficial uses including clean drinking water (public water supply) and recreation (primary and secondary contact), aquatic and wildlife habitat and fish consumption, agriculture, and other uses (EPA 2005a).

The Safe Drinking Water Act (1974) established public drinking water standards, enforceable by law, for various contaminants detrimental to human health. Primary contaminants include a wide variety of classes: disinfection byproducts, disinfectants, inorganic chemicals such as heavy metals and nitrate, organic chemicals such as herbicides and industrial discharges, and radionuclides such as uranium (EPA 2005a). Acceptable levels were developed and are published for each contaminant.

Water quantity and water quality are rapidly becoming a serious problem in the Intermountain West and other arid regions of the western United States. Over one hundred years of riparian degradation by livestock, dams and water diversions, and irrigation return flows have contributed to degradation of the region's streams and rivers. Increasing urbanization accompanying unprecedented population growth are pushing water resources to their limits in many communities. In conjunction with these issues, a prolonged drought (1998-2004) has created an immediate need for management practices to address these water problems.

There is substantial research data to suggest that riparian buffers (linear vegetated areas along rivers, streams and other water bodies) are a cost effective tool in mitigating water quality problems. However, most of the research on riparian buffer effectiveness has been done in landscape regions beyond the Intermountain West. Intermountain West resource managers have expressed a need for a buffer planning protocol and design guides that meet the unique characteristics of this region (Johnson and Buffler 2005).

The data synthesized in the literature review and identification of unique Intermountain West landscape characteristics affecting buffer functions provided the foundation upon which Buffer Design Guidelines for Water Quality and Wildlife Habitat Functions on Agricultural Landscapes in the Intermountain West (Riparian Buffer Handbook) was developed.

The Riparian Buffer Handbook is a resource for:

- assessing the functional condition of existing riparian buffers and the off-site conditions to be buffered
- determining the applicability of buffers to address these conditions
- determining buffer appropriateness, general buffer design guidelines and management strategies, buffer configuration and structural characteristics to meet water quality and wildlife objectives

Every riparian buffer and adjacent upland site condition will have unique aspects making it difficult to develop universally applicable planning and design guidelines, however, many site characteristics and adjacent land uses are similar throughout the region and are familiar to area resource managers. In these settings the riparian buffer design protocol and guidelines presented in the Riparian Buffer Handbook can be used by resource managers. Inevitably, atypical buffer situations will be encountered; expert advice from conservation partners, extension water quality specialists, Natural Resource Conservation Service (NRCS) personnel and other state and county agencies should be solicited.

Currently, the Conservation Security Program (CSP) administered by the NRCS, provides funding and assistance on agricultural lands for practices that promote or maintain the "conservation and improvement of soil, water, air, energy, plant and animal life, and other conservation purposes on Tribal and private working lands. Working lands include cropland, grassland, prairie land, improved pasture, and range land, as well as forested land that is an incidental part of an agriculture operation" (NRCS 2005). Water quality practices funded by the CSP include conservation tillage, filter strips, terraces, grassed waterways, managed access to water courses, nutrient and pesticide management, prescribed grazing, and irrigation water management.

Protection of riparian areas (buffers) on private cropland and mixed cattle / crop systems in the sagebrush steppe region of the Intermountain West can be fiscally feasible for many private landowners. They have access to cost-share for planning and implementation programs such as the Conservation Reserve Program (CRP), Wildlife Habitat Improvement Program (WHIP) and Environmental Quality Improvement Program (EQIP). In addition, the NRCS offers technical assistance to landowners and frequently helps build funding partnerships with Non governmental organizations (NGOs) (NRCS 2005). Partnerships will be key to implementing riparian buffer projects.


Photo credit: Susan Buffler

Canoeing on the Bear River, Cache Valley, UT

Background

Historically, waterways and riparian areas have always attracted humans (Busch and Scott 2004). Hunting, fishing, the development of agriculture, cities, transportation networks, and recreation, has traditionally occurred in these areas. Human impacts on riparian systems, particularly in the Western United States, have been considerable. It is estimated that over 70 percent of western riparian habitat has been significantly altered or eliminated by draining, clearing, permanent flooding, diverting and damming (Gardner et al. 1999; NRC 2002).

In the western United States, cattle grazing alone accounts for 80% of damaged stream and riparian systems (Belsky et al. 1999). Cattle tend to congregate in cool, shady riparian habitat where forage availability and quality is high (Clary and Medin 1992). In many cases, exclusion from riparian areas has been successful in restoring riparian areas to proper functioning condition (BLM 1997). Other low impact rotational grazing management systems such as Holistic Resource Management (Savory and Butterfield 1999) and seasonal rest rotation of cattle and sheep have been shown to improve riparian function (BLM 1997). However, Belsky et al. (1999) in their review of livestock influences on stream and riparian ecosystems argue that nothing short of complete exclusion will return riparian areas to their proper functioning condition.

Agricultural land uses contribute the majority of non-point sources of pollution leading to degradation of surface and subsurface waters

(EPA 2000 Chapter 10). Contaminants originating in agricultural landscapes include sediment, fertilizers, herbicides and pesticides, organic and inorganic compounds, bacteria and viruses, hormones and antibiotics (Barfield et al. 1998; Belt et al. 1992; Dillaha and Inamdar 1997).

Riparian areas function in maintaining ecological processes such as: regulating stream temperature, stream flow, cycling nutrients, providing organic matter, filtering chemicals and other pollutants, trapping and redistributing sediments, stabilizing stream channels and banks, absorbing and detaining floodwaters, maintaining fish habitats, and supporting the food web for a variety of biota, and regulating stream temperature (Wenger 1999; Fischer et al. 2000; Obedzinski 2000; CRA 2001; NRC 2002: Chambers and Miller 2004). Thus protection of existing functional riparian systems and restoration of degraded systems can be one tool employed to address water quality issues.

Unfortunately, unlike wetlands, riparian areas are not protected under Section 404B1 of the Clean Water Act mainly because there is no currently agreed on definition for a riparian area (NRC 2002). The definition used by the National Research Council (NRC) is a first step in initiating a process to define riparian areas by their function and ecological processes. The definition used by the NRC is appropriate for the Intermountain West since it is comprehensive but also general enough to be used for different physiographic regions.

> **"Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e. zone of influence). Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine-marine shorelines."** (NRC 2002)

Although riparian buffers have been shown to be effective in improving water quality, the current state and federal buffer width recommendations are generally not based on scientific consensus but on political acceptability (Dillaha and Inamdar 1997; Fischer et al. 2000; Fischer and Fischenich 2000) and ease of conservation program delivery.

Developing buffer width guidelines based on scientific data that are responsive to regional landscpae characteristics is essential to long term enhancement of water quality in the region. Buffers are particularly effective when combined with other conservation practices.

Cattle grazing on a remnant riparian area. Bear River, southeastern Idaho. Photo credit: Susan Buffler

Project Goal

The goal of this document was to synthesize the riparian buffer literature into a format that:

- identified the most important landscape attributes affecting buffer width and design
- identified unique Intermountain West landscape characteristics that will affect buffer width
- identified a planning protocol that could be adapted to western landscpape conditions, utilizes readily available or easily measured data, is scientifically defensible, easily replicated and is easily implemented in the field

To accomplish this goal, a buffer planning protocol, must respond to those Intermountain West landscape characteristics most important in resolving water quality issues. These include: hydrological characteristics of the watershed, adjacent land use and land management practices, general soil characteristics, slope gradients, vegetation and surface roughness, climate, runoff characteristics, fish and wildlife species needs, and recreation activities (Buffler 2005). The planning protocol and guidelines must also be flexible enough to respond to atypical site conditions that may be encountered in the field.

Specific intended riparian buffer functions addressed in the water quality portion of the proposed planning protocol are to reduce impacts to water quality from adjacent land uses by reducing sedimentation and pollution of surface water and contamination of shallow ground water.

The Riparian Buffer Handbook should be used as a tool by land managers in conjunction with other Best Management Practices (BMP) to improve water quality. Buffers in and of themselves are not a panacea for all water quality improvements.

The NRCS and resource planning professionals are increasingly involved in watershed scale planning of which buffers are a small part. The reality, however, is that funding for buffer projects tends to be allocated one landowner initiated buffer at a time making contiguous buffering problematic but not impossible.

Methods

Several tasks were required to achieve the broad goals outlined above. The first was to delineate an appropriate study area. Delineation of a study area within the Interior Western states was determined through identification of regions with general similarity in: soils, climate, vegetation, hydrology wildlife, and cropping and grazing systems.

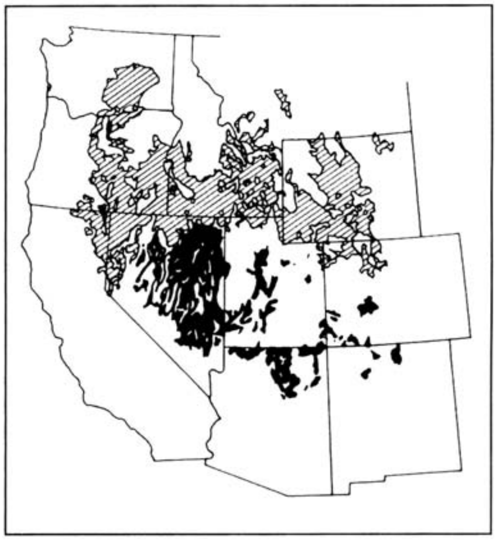
The second step, the largest task, was to review literature relevant to riparian buffers. This review included books, journal articles, technical publications and gray literature. In addition soil scientists, range scientists, ecologists and wildlife biologists from the Intermountain West with expertise in conservation buffers were interviewed. Several protocols for estimating the general condition of riparian habitat ecosystem function, and structure were reviewed.
In order to identify appropriate buffer widths and design guidelines for riparian buffers on private lands in the Intermountain West, these steps were followed.

1. Delineate the region of interest
2. Review, inventory and catalog available relevant riparian buffer literature
3. Focus on:
   a. Buffer retention of sediment, nitrogen, phosphorus, pesticides, and pathogens. Each of these is described and a matrix of relevant research compiled.
   b. Unique characteristics of riparian ecosystems in the Intermountain West.
4. Query major professional societies, non-governmental organizations (NGOs), and government agencies about riparian buffer guidelines
5. Review findings with the National Agroforestry partners
6. Review of guidelines prepared in this research by outside experts

Research results from the literature reviewed were organized into a series of tables. A table was prepared for each type of contaminant. An additional table displays research findings on buffer effects on surface and subsurface flows.

Characteristics of the Study Area

The study area is large and complex; a picturesque landscape with valleys of varying sizes and broad plains enclosed or edged by tall mountains. Elevations range from over 13,000 foot mountain peaks to valleys at 3,000 feet. Precipitation varies from more than 50 inches in upper watersheds to less than six inches at lower elevations and in mountain rain shadow areas. Desiccating winds are strong and persistent. Wind and runoff generated soil erosion is prevalent on open exposed landscapes throughout the study area.



Map of the study area. Adapted from West 1988. Cambridge Press

Forest and range land, most in public ownership, predominate in the upper reaches of area watersheds. Range land is also dominant in the broad lower elevation plains and drier southern and western sections of the study area. Rolling foothills and relatively flat valleys often with fertile soils, a sufficient growing season and access to water for irrigation are typical of cropped lands in lower reaches of most watersheds.

These more agriculturally productive lower elevation landscapes support row crops, orchards, dairy and ranching activities. Riparian buffers in these working landscapes are the focus of this project. Working landscapes in the study area are populated by scattered farms and ranches supported by small rural communities. Historically agriculture, ranching and tourism have been the mainstays of the Intermountain West economy. However a transformation is in progress fueled by a declining farm and ranch economy. Regional economies are diversifying. Unprecedented urban and exurban growth, much of it occurring along riparian corridors, is consuming farm and ranch land, and wildlife habitat, and converting it to suburban tracts and upscale ranchettes. This new land use dynamic combined with old riparian resource issues (grazing, logging, mining, and recreation) present planners and resource managers with complex challenges.

Riparian Buffer Complexity and Dynamics

Riverine systems are multidimentional (longitudinal, lateral and vertical) complex and change over time. Climate influences the entire system. Geologic and topographic features define the watershed. Watershed hydrology, surface, subsurface and stream flows affect and are affected by riparian buffer plant communities. All of these factors are subject to modification by human activity. The following discussion highlights several key riparian buffer structural and functional characteristics that affect riparian buffer vegetation and water quality.

At the stream reach (buffer project scale), bank storage, or channel water moving into the riparian zone influences not only water storage, chemical transformations, and surface water temperature but may also greatly affect the composition and extent of plant communities (NRC 2002). Alteration of the flow regime by water impoundment, diversion, or groundwater withdrawals has significantly reduced native riparian vegetation in many parts of the West. Once this occurs, salinity may increase (Stromberg 2001) and weedy species, particularly mesic and often non-native trees, gain a foothold and are difficult to remove (Busch and Scott 2004). Decline in groundwater may isolate patches of native vegetation leading to their disappearance (Busch and Scott 2004). Restoration becomes more difficult; native cottonwoods, for example, require specific peak flows for establishment and reproduction and higher water tables for long-term survival.

A riparian vegetation study done on the Snake River, Idaho revealed that approximately 30% of the flora and 60% of the tree basal area and density was composed of exotic species. Only two regionally native tree species were found. Adjacent agricultural uses had eradicated or severely reduced native species in the upland areas of the downstream section of the river (Dixon and Johnson 1999). An increase in woody vegetation over time, mainly on in-stream islands, was observed. It was speculated that reduced low flows from damming over a period of about 80 years and increased sedimentation from agricultural practices created larger island and mainland riparian areas. Introduction of exotic trees with different reproduction and establishment requirements may also have contributed to the increase of exotic species (Dixon and Johnson 1999). This pattern was also found on rivers and streams in Arizona that have not been diverted but where flooding has been controlled (Stromberg 2001).

Riparian vegetation from the canopy, woody debris, roots and leaf litter, helps stabilize stream banks by protecting the soil surface from impacts of rain and increases infiltration through soil macropore formation (NRC 2002). However, once vegetation is removed, surface cover and root strength are reduced, increasing erosion and often concentrating overland flow; surface erosion may occur during storm events, particularly with increasing slope (NRC 2002).

Deep rooted plants have better soil holding capacity than shallow rooted plants (Schultz et al. 1994), however, historically occurring native grassed riparian zones on streams in the Great Plains, may have greater bank holding properties on streambanks with low slopes, due to their fibrous root systems (Lyons et al. 2000). Streambanks with steeper slopes are better stabilized by woody vegetation. Grass and wooded riparian areas have different structures (Table 1). For instance, grassed streambanks store significantly more sediment than wooded streambanks, are narrower, and tend to produce undercut banks favored by fish. Wooded riparian areas provide fish habitat and energy inputs through debris falls and may have lower summer baseflows due to higher water uptake by vegetation (Lyons et al. 2000; Cushing and Allan 2001).

Naturally meandering streams with adequate vegetation for bank stabilization are more effective for flood control than channelized streams because stream flow is reduced (Fry et al. 1994). Natural inputs of woody debris to the stream can cause localized flooding but downstream flooding may be reduced (Lyons et al. 2000). Natural streams are also more capable of initiating and sustaining communities of native riparian plants and wildlife.

Table 1. Relative effectiveness of different vegetation types for providing specific buffer benefits.

Benefit	**Grass**	**Shrub**	**Tree**
Stabilize bank erosion	low[1]	high	high
Filter sediment	high	low	low
Filter sediment-bound nutrients, pesticides, microbes	high	low	low
Filter soluble nutrients, pesticides, microbes	medium	low	medium
Aquatic habitat	low	medium	high
Wildlife habitat range/ pasture/ prairie wildlife	high	medium	low
Forest wildlife	low	medium	high
Economic products	medium	medium[2]	medium
Visual diversity	low	medium	high
Flood protection	low	medium	high

[1] slope dependent

[2] includes decorative woody floral industry

NRCS 2005

Nutrient cycling

Complex cycling of nutrients between soil minerals, microbial components, and plants is also characteristic of riparian areas. Major nutrients such as nitrogen, carbon, and phosphorus are the most important in the function of natural riparian ecosystems (Baker et al. 2004).

Riparian vegetation strongly affects nutrient cycling in aquatic systems. Plant litterfall and large woody debris is broken down by physical action and by in-stream organisms providing a carbon energy source in the form of coarse particulate organic matter (Cushing and Allen 2001; Baker et al. 2004). Plant roots release carbon and decaying cells to supply an energy source to soil microbes, thereby increasing mineralization activity. Release of nitrogen from decaying plant tissues through mineralization is lower in arid areas except where irrigation is practiced and large quantities of vegetation are available (Brady and Weil, 2000). Riparian areas may act as a source or a sink, releasing or holding nutrients depending on riparian management (phosphorus and sediment) as well as seasonal factors (nitrogen) (Wenger 1999).

Properly functioning riparian buffers are more effective at maintaining or enhancing water quality than impaired buffers (Buffler 2005).

Landscape Attributes Influencing the Effectiveness of Riparian Buffers; Implication for Intermountain West Buffers

Although general and brief, the previous discussion makes an important point; numerous site attributes affect riparian buffer function. Each attribute could therefore affect decisions regarding appropriate buffer widths to protect water quality.

Literature reviews as cited in Kleinschmidt Associates (2000) and completed by Buffler (2005) suggest there are several landscape attributes (primary attributes) that have the most significant influence on riparian buffer effectiveness and width. They are introduced briefly below.

Primary Attributes

Buffer Width

Developing a protocol for determining appropriate buffer widths for water quality is the primary goal of this project. Because of its importance, width and its relationship to reducing sediments, nitrogen, phosphorus, pathogens, and pesticides is mentioned here and discussed in greater detail later in this chapter.

According to Gilliam et al. (1997), buffer width is the most important **controllable** variable in determining effectiveness of buffers in reducing pollutants and protecting stream health with most of the beneficial effects of buffers occuring within the top upslope half of the buffer (Peterjohn and Correll 1984; Lowrance 1992; Jordan et al. 1993; Robinson et al. 1996; Lim et al. 1998; Schmitt et al. 1999; Jin and Römkens 2001; Syversen et al. 2001).

Buffer widths for streams in more arid areas may need to be wider due to the different nature of western stream systems. For example, higher order valley streams typical of the study area tend to be wider with less vegetation overhanging the stream, therefore, a different stream ecosystem results (Gilliam et al 1997; Lyons et al. 2000). Fry et al. (1994) suggests that since arid rivers move more freely throughout their floodplains than those in wetter regions, buffer widths should range from 23m to 35m. This is particularly relevant where streams are intermittent and summer storms are short and intense.

Slope Gradient

Few studies reviewed compared different slope gradients with levels of contaminant removal. A 6m (19.7’) buffer on a Montana riparian pasture reduced sediment at 3m (9.8’) on slopes ranging from 2 to 20% (Hook 2003). Jin and Römkens (2001) found no increased trapping efficiency on a simulated buffer beyond 3m on a 4 or 6% slope. Davies and Nelson (1994) found that in logged forests effects on sedimentation depended on buffer width, not on slope, erodability, or time.

However, on sites where nitrogen, dissolved phosphorus, pathogens, and pesticides need to be attenuated wider buffers may be required on steeper slopes, although Jones (2001) found weak correlations between slope and nitrogen removal in three California riparian buffers. Other studies show a less clear trend with some contaminants decreasing with decreasing slope (Patty et al., 1997). Sites with slopes steeper than 25% with little surface roughness or infiltration capacity probably need wider buffers (Kleinschmidt 1999).

Soil Infiltration

Soil infiltration is important in removing fine sediment, nitrogen, and certain pesticides and pathogens (Kloppel et al.1997; Barfield et al. 1998; Arora et al. 2003; Boyd et al. 2003). Antecedent conditions also affect runoff rates. Water flowing over saturated soils will more likely bypass potential subsurface transformational processes (Daniels and Gilliam 1996; Hill 1996).

Soil texture and structure influence infiltration. Many of the soils in valleys of the Intermountain West have a strong clay component. Clay soils, comprised of small particles, have lower infiltration rates, but higher water holding capacity than gravelly, sandy, or loamy soils (Leopold 1997; Brady and Weil 2000; NRC 2004) thus reducing buffer effectiveness.

Surface Roughness

Surface features such as coarse woody debris, rocks and boulders, vegetation, and other microtopographic features, reduce overland flow in woody and mixed vegetation buffers (Kleinschmidt 1999). Sites with high levels of surface roughness increase infiltration of surface runoff reducing overland flow and thus decreasing the amount of contaminants to the stream. Reduced overland flow can, therefore, reduce buffer width required for water quality functions.

Slope Length (Discussion)

Slope length was not considered to have as important an effect on buffer width as slope gradient. As noted above and elsewhere in this appendix, most attenuation of contaminants with the exception of nitrogen, occurs within the first 20m (60’) of the buffer. The minimum buffer width recommended in the Riparian Buffer Handbook based on the literature review and assessment of Intermountain conditions is 70’ (21.3m) or top of stream bank plus 35’(10.7m), whichever is greater, thus slope length was not considered a primary attribute for determining buffer width because attenuation occurs within the minimum length recommended.

Adjacent Land Use Practices

Adjacent land use and management practices can have a significant effect on the quantity of pollutants that reach the buffer (Kleinschmidt Associates 1999). Planting perpendicular to the slope as opposed to conventional vertical tillage has been shown to reduce herbicide runoff from cultivated fields (Patty et al. 1997). Implementing NRCS in-field and range conservation practices such as terraces, in-field buffers, grassed waterways, and rotational grazing have proved effective at reducing contaminants before they reach riparian buffers (Buffler 2005). Minimizing the application of fertilizers, and pesticides adjacent to buffers (especially phosphorus) is preferable since buffer function may decline over time if they become overloaded with chemicals (Wenger 1999). Wider buffers may be required where in-field conservation practices are not implemented.

Secondary Attributes

Secondary attributes are landscape features that affect buffer effectiveness and width but to a lesser degree than Primary Attributes. Secondary Attributes identified in the literature include:

- surface water features
- sand and gravel aquifers
- seeps and springs
- floodplains
- wetlands

Secondary attributes are frequently used to modify (expand) preliminary widths delineated using primary attributes alone (Kleinschmidt 1999).

Differences Between Arid and Non-Arid Riparian Systems - Effects on Buffer Attributes and Width

The functional characteristics of site attributes are different in arid and non-arid environments. These differences must be understood when interpreting buffer width research findings from non-arid environments and assessing their applicability to riparian buffers in the arid Intermountain West.

Climate

The major differences between riparian areas in arid and mesic regions are driven by climate. Arid regions of the United States are found approximately between the 100th parallel and the Cascade and Sierra Nevada Ranges of the coastal states of California, Oregon, and Washington. Low precipitation, cold winters, and hot windy summers characterize the high desert regions of the Intermountain West and are generally dominated by high pressure (Obedzinski et al. 2001; Malanson 1993).

Amount and seasonal distribution of precipitation differs between arid and mesic regions. Precipitation in the arid Intermountain region ranges from less than 5 inches (127mm) to greater than 60 inches (1,524mm) in the higher elevations with evapotranspiration exceeding transpiration (WRCC 2004).

Many of the water sources in the west originate in the mountains as snowmelt and from summer monsoons (Fry et al. 1994; Cushing and Allan 2001). Biomass production tends to be lower in arid than in mesic regions and short-term effects such as summer rains can further influence biomass production and cover (Malanson 1993; Stromberg 2001). Long-term drought and moisture cycles of several hundred years have also been documented, altering flow regimes and vegetation patterns over time (Obedzinski et al. 2001).

Lower precipitation and periodic drought in the west coupled with lower stream flows and modified flood cycles due to damming or diversion makes recovery of damaged riparian systems more difficult due to increased stress from lowered water tables. Restoration of uplands damaged by grazing and other detrimental land use practices is critical for restoration of riparian areas as well (Stromberg 2001). Irrigation return flows are common in arid regions and are often contaminated with herbicides and excess nutrients. This source of water can be used for restoration, however, if these inputs are reduced or eliminated.

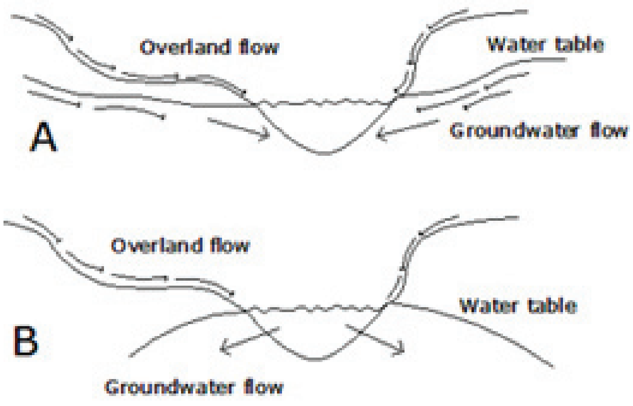
Hydrology

Hydrology is the largest factor controlling effectiveness of buffer function (Gilliam et al. 1997). Overland flow is the predominant hydrological characteristic in buffers in the Intermountain West. Attempts should be made to eliminate the effects of channelization which increase flow velocity and reduce or negate buffer effectiveness. Long-term effects of overland flow such as sediment build up along field edges may cause flow to migrate around the edge creating channels through the buffered area (NRC 2002) while periods of intense rainfall, common in the Intermountain region, may quickly create channels due to the heterogeneity of the terrain (Dosskey 2002). To increase buffer effectiveness, design criteria should include methods for promoting sheet flow through the buffer (Gillliam et al. 1997).

Riparian areas provide important connections between surface and subsurface waters (NRC 2002) which profoundly affect the transformation, infiltration, and / or containment of contaminants. Interactions between the stream channel and groundwater, however, are not the same along the channel length (NRC 2002).

Water movement into streams in the Intermountain regions is more likely to come from overland flow because of lower levels of vegetative cover and soils high in clay content (Baker et al. 2004). In low order mountain streams water moves into the channel through groundwater but out of the channel in higher order valley streams (effluent or losing stream). In more mesic areas, water moves into the stream channel (influent or gaining stream) mainly through groundwater. Maintenance of streams in the Intermountain West is dependent on snowmelt supplies (NRC 2002). Groundwater flow contributes more than overland flow in mesic areas with their greater vegetative biomass and more consistent precipitation (Malanson 1993; Baker et al.2004).

Figure 2. Comparison of mesic (A) and arid (B) stream hydrology.



(Susan Buffler: adapted from Malanson 1993 and Baker et al. 2004).

Soils

Valley soils tend to be shallow and more saline in arid regions, particularly where irrigation in riparian floodplains is practiced (Fry et al. 1994; Stromberg 2001). They are high in clay content and have low infiltration rates. Soils in general tend to be nitrogen limited, since denitrifying bacteria rarely have adequate conditions for optimal function (Mee et al. 2003).

Topography

Much of the Intermountain West is characterized by high elevation mountain ranges interspersed with broad, flat valleys. Riparian buffer plant communities vary with elevation and topographic aspect due to temperature change, increased soil moisture at higher elevations and shaded topographic aspects (Grimm et al. 1997; Mee et al. 2003). Lateral stream bank slopes are frequently steep, a product of channel inclusion.

Vegetation

Hydrology and geomorphology play a major role in the development and maintenance of vegetation types in arid regions (Gardner 1999; Stromberg 2001). Vegetative cover is typically less dense in arid and semi-arid regions, reducing infiltration and increasing the likelihood for faster overland flow, particularly with increasing slope and other topographic features.

A strong increase in the depth to water table with increasing distance from the stream dictates which vegetation types will occur in the riparian zone (Stringham et al. 2001), therefore, vegetation is often taller in riparian areas than in the surrounding matrix (Malanson 1993). Woody vegetation surrounds riparian areas and other water supplies such as lakes and cold desert springs (Malanson 1993; Cushing and Allan 2001; CRA 2001).

Riparian vegetation, however, is composed of narrow bands of trees and shrubs competing for the relatively large water supply (Malanson 1993: Baker et al. 2002; NRC 2004). Large woody vegetation tends to decline rapidly with increasing distance from the stream following the pattern of the water table (Malanson 1993).
Vegetation in these regions tends to be more distinct than in other regions of the United States with stronger delineations between riparian and upland zones (Malanson 1993).

Plant density is lower in the Intermountain West, due to the lack of rainfall. Soils in the Intermountain West are often shallow and coarse and unable to hold much moisture, and therefore, vegetation is sparse supporting drought tolerant shrubs, grasses, and herbaceous species in the plant community (Mee et al. 2003). Shrub steppe is the predominant plant community in the study area. The shrub steppe region of the Intermountain West ranges from 4,000 to 6,000 feet (1219 to 1828m) with no dominant tree species. Plant cover ranges from about 50 to 75% (Mee et al. 2003). Few studies have been done on riparian ecophysiology in the Intermountain West (Dawson and Ehleringer 1991). Plant species diversity tends to be lower in intermittent and ephemeral than in perennial channels in riparian areas in arid lands (Stromberg 2001) leading to greater fragility when groundwater is reduced. Species richness is also more heterogeneous due to moisture limitations and variability (Tabachhi et at. 1998).

Plants in the Intermountain West are more commonly dieoceous, having male and female individuals (Dawson and Ehleringer 1993). Female trees were disproportionately found in non-stressful sites closer to the stream but had lower water use efficiencies than male trees. Dawson and Ehleringer (1991) also found that mature Boxelder (*Acer negundo*) trees used deep groundwater instead of stream water even when close to the stream. Youngest trees near the stream used stream water but young trees farthest from the stream used water from precipitation. Possible explanations include wide ranging stream channel movement and undependable stream water flows.

Wildlife

Riparian systems in arid regions account for less than 1% of the land area but 70% of wildlife species (Fry 1994; Belsky 1999; CRA 2001). Over 80% percent of all bird species in the Great Basin are either dependent or partially dependent on riparian areas while 51% of bird species in the Southwest are totally dependent on these areas (Gardner et al 1999). Species diversity in the western U.S. can be as great as that in the east. Herbivory by deer, elk, moose, and beaver can have significant adverse effects on riparian vegetation and consequently buffer effectiveness.

Table 2. Summary of the main differences of riparian areas between arid and non-arid regions.

Climate	• low precipitation levels occurring mainly in winter and summer monsoons • short duration, high intensity rainfall • evapotranspiration exceeds precipitation • hot, dry, windy summers • cold winters • dominated by high pressure in summer • long and short term drought cycles
Hydrology	• regulated stream flows and diversions • maintenance of streamflow dependent on snowmelt • higher order valley streams tend to be effluent (water moves out of the stream channel) • overland flow predominates
Soils	• shallow saline soils • high clay fraction • low infiltration
Topography	• mountain ranges interspersed with broad flat valleys • frequent steep gradients
Vegetation	• low biomass production • low plant density (cover ranges from 50 to 75%) • plant communities vary with elevation • vegetation decreases with increasing water table depth • woody vegetation predominates in riparian areas along lower elevation higher order streams • low surface roughness is common
Wildlife	• riparian areas account for 70% of wildlife species • over 80% of birds are dependent or partially dependent on riparian areas • high species diversity • herbivory can be high and adversely affect riparian vegetation

The conclusions drawn from comparing riparian buffer attributes in arid and non-arid environments is that in the Intermountain West:

- overland flows are higher, more intense and shorter lived
- infiltration rates are lower
- plant density and surface roughness are slower

The buffer width implications of these differences is that riparian buffers in the Intermountain West need to be wider to meet water quality objectives.

Sources and Causes of Impairment

Nationwide, approximately 19% of total stream miles have been assessed by states and tribes in their 2000 305b reports (EPA 2000a), 39% of these streams were considered impaired. Fifty percent of the streams in the Great Basin are impaired to some extent (Chambers et al. 2004). Losses in Utah are undocumented (Gardner 1999). Significant numbers of stream miles in the study area are impaired for one or more beneficial uses (Table 3, 4).Agriculture, stream modifications and habitat alteration are the top three contributors to impairment of surface and subsurface waters. Agriculture accounts for 48% of the impairment to streams (EPA 2005). Leading contaminants from these agricultural sources include pathogens (bacteria), sedimentation, habitat alterations, oxygen-depleting substances, nutrients, thermal modifications, metals, and flow alterations. Pathogen contamination accounts for 35% of water quality impairment.

Loss of riparian areas and thus their buffering and bank stabilizing functions are difficult to determine but it is estimated that 85% to 95% percent of riparian habitat in Arizona, New Mexico, and California have been lost (NRC 2002). Agricultural practices such as inappropriate grazing, fertilizer treatments, irrigation return flows and recreation associated impacts are the main sources of riparian habitat degradation in the study area (EPA 2000b). Invasive exotic plants, such as tamarisk (*Tamarix ramosissima* Deneb.) have also influenced the distribution of native riparian vegetation and degraded riparian habitat.

Table 3. Major causes of stream impairment in the study area by state.

	ID	MT	OR	UT	WA	WY
Pathogens (Bacteria)	X		X		X	X
Flow alterations	X	X				
Nutrients	X	X		X		
Siltation	X	X				
Thermal modifications	X		X		X	
Habitat alteration		X	X	X		
Metals		X			X	X
Total dissolved solids				X		
pH					X	
Low dissolved oxygen					X	

Adapted from EPA 2000b
ID - Idaho, MT - Montana, OR - Oregon, UT - Utah, WA - Washington, WY - Wyoming

Irrigation operation on the Bear River, Cache Valley, UT. Photo credit: Susan Buffler

Table 4. Percent of impairment for designated use per stream miles assessed by state.

State	Stream miles assessed	Designated use*	% impaired	Impairment source
ID	17,333	Aquatic/ wildlife	47%	Not determined
MT	8,714	Aquatic/ wildlife	3%	Agriculture Resource extraction
	7,066	Recreation	49%	
OR	114,823	Aquatic/ wildlife	26%	Agriculture, silviculture, habitat and hydrologic modifications, hazardous waste sites, urban runoff
	5,062	Recreation	44%	
	984	Fish consumption	81%	
UT	10,465	Aquatic/ wildlife	16%	Agriculture, nutrients, sediment
	518	Recreation	2%	
WA	70,439	Aquatic/ wildlife	40%	Agriculture, hydrologic, habitat modification, natural sources, and septic tanks
	70,439	Recreation	16%	
	58,990	Fish consumption	74%	
WY	2,640	Aquatic/ wildlife	7%	Unknown sources, agriculture, and natural sources
	252	Recreation	100%	

*fish, shellfish, and wildlife protection and propagation. (adapted from EPA 2000b)

Contaminants and Buffer Effects

Contaminants can be classified generally as either dissolved or particulate. The major dissolved contaminant from agricultural lands is nitrogen (N) while the major particulate contaminant is sediment and sediment-bound chemicals and nutrients. Phosphorus (P) is found in particulate and dissolved form while pesticides are mainly associated with sediment and are dependent on their adsorption capacity to sediment particles. Pathogens are mainly associated with sediment and are dependent on retention in the soil, infiltration and water flow.

Buffer designs are tailored to address non-point source pollution that include nutrients, agricultural chemicals, pathogens from animal waste and sediment, however, a continuing concern is the bypass of contaminants through the buffer either directly or through naturally occurring hydrological characteristics of the buffer. In some cases, riparian buffers are ineffective in reducing contaminants from adjacent land uses and alternative best management practices should be implemented. For example, a ten year study on Rock Creek, Twin Falls, Idaho (Maret et al. 1991) documented significant improvement in water quality when BMPs including riparian buffers were implemented. However, irrigation bypass and tail waters laden with pollutants (an estimated 14% of the water diverted) returned to the stream at some point below the diversion. This is an important area not covered in this document that requires further study.

Particulate Contaminants - Sediment

Sediment entering rivers and streams is a natural phenomenon critical to buffer function and structure and stream morphology. However, when quantities of sediment entering the stream exceed the normal range, buffer function and structure, and water quality can become impaired. Buffer function and structure are also impaired and stream channel dynamics altered when normal sediment loads in the stream channel are reduced or eliminated by dams or diversions.

Reasons for concern

Sediment is a leading contaminant of streams in the Intermountain West (EPA 2005). Sediment often originates from upland land management practices and, if not altered or buffered, can have significant impacts on stream water quality. Excess amounts of sediment in streams physically reduces light infiltration and thus algae production and habitat and food for other aquatic organisms (Wenger 1999; Mason 2000). Some pesticides and phosphorus can adsorb to soil particles and be carried into streams through erosion and runoff (Harris and Forster 1997). Sedimentation is also a significant factor in reducing the storage capacity of reservoirs.

Livestock damage to stream banks accounts for a significant amount of riparian and stream bank damage in consequent sediments entering the stream (Belskey 1999). Livestock trample vegetation and physically damage stream banks due to pressure from hooves. Excessive trampling breaks down stream banks resulting in flattened bank angles, a reduction in bank undercutting and accelerated erosion (NRC 2002; Baker et al. 2004). Vegetation is damaged or killed causing root loss destabilizing stream banks and accelerating stream widening (NRC 2002).

Improper grazing also contributes to soil compaction, destruction of biological crusts, and introduction and distribution of exotic plant species. Indirect impacts include, alteration of fire regimes, increased erosion, changes in infiltration rates, runoff and water holding capacity, changes in plant competition patterns and reproductive success (NRC 2002). These in turn may lead to changes in stream width, depth, bank water depth and the composition of bed material. Water quality is reduced through increased suspended sediments and in-channel deposition (Stromberg 2001).

Other factors that influence sediment dynamics of the stream include watershed management (Wenger 1999; Rhodes et al. 2004), damming and diverting streams, mining, construction sites, road construction, and forestry practices (Wenger 1999; Baker et al. 2004; NAC 2004). Peak flows, sediment, and channel migration are reduced downstream of dams. This leads to decreases in vegetation structural complexity, decreased biodiversity, and unwanted plant and animal species (Baker et al. 2004).

How buffers affect sediment

Riparian buffers can be effective for trapping or displacing sediment (Dillaha and Inamadar 1997) and stabilizing stream banks to reduce erosion, and providing large woody debris in the stream channel for sediment trapping (Wenger 1999). Both grass and forest buffers are useful for trapping sediment. The processes of deposition and infiltration act to remove sediment; with smaller clay particles removed by infiltration. Factors influencing buffer effectiveness include, width, length, sediment load, flow rate, slope, grass height and density, surface roughness, and degree of vegetative submergence (Belt et al. 1992; Dillaha and Inamadar 1997).

Most studies (Matrix A) found that larger particle sizes in sediment are deposited in the first 3 to 10m of the buffer while smaller sized particles may be transported and deposited or infiltrated farther overland into the buffer (Chaubey et al. 1994, 1995; Robinson et al. 1996; Barfield et al. 1998; Mendez et al. 1999; Schmitt et al. 1999; Sheridan et al. 1999; Lee, Kye-Han et al. 2000; Syversen et al. 2001; Hook 2003). Dosskey et al. (2002), however, found that areas with heterogeneous topography may not reduce sedimentation significantly due to increased channelized flow. Sediment can build up at the field / buffer interface and create a dam or berm. Overland flow is then diverted around the berm, creating channelized flow through the buffer (Wenger 1999). Daniels and Gilliam (1996) also found that buffers were overwhelmed by high flows. In these cases, buffers inappropriately designed or maintained can become a source of sediment. Long-term trapping may not be feasible without periodic sediment removal. Grass buffers, although more likely to be inundated by exceptionally high levels of sediment, are useful in maintaining sheet flow and preventing rill and gully erosion. Forest buffers have other advantages and a combination of grass and forest is usually recommended (Wenger 1999).

Particulate Bound Phosphorus (P)

Phosphorus is essential for energy transfer, protein synthesis and other metabolic processes and is a component of deoxyribonucleic acid (DNA) (Brady and Weil 2000). Phosphorus, although generally occurring in adequate amounts in the Intermountain West, tends to fix to soil particles when applied to crops in soluble form. Over-application of synthetic fertilizers and manure tends to occur leading to a buildup of phosphorus in the soil (Brady and Weil 2000; Hart et al. 2004).

Phosphorus is found in both organic and inorganic forms and is either sediment bound or dissolved (Hart et al. 2004). Since most P is readily adsorbed to mineral and organic soil particles, its removal in buffers tends to follow the same patterns as sediment (Uusi-Kamppa 1997; Zheng 2004). Factors affecting retention of P are: kinetic factors, particle size, adsorption capacity of the soil, contact time, and temperature (Uusi-Kamppa 1997).

Reasons for Concern

Phosphorus can contribute to eutrophication or “the enrichment of waters by inorganic plant nutrients” (Mason 2002; Zheng et al. 2004). Increased algal blooms create low oxygen conditions due to decay of organic material and reduce fish and plant diversity (Hart et al. 2004).

How buffers influence P dynamics

Riparian buffers can be effective in reducing the amount of sediment bound P (Gilliam 1994). Increasing buffer width, in general, reduces particulate P (Chaubey et al. 1994, 1995: Daniels and Gilliam 1996: Lee et al. 2000). Because P is stored in buffers and is not transformed, it is susceptible to being remobilized, therefore, where high flows may overwhelm filters, (Daniels and Gilliam 1996) (Matrix C), additional best management practices to reduce P before it enters the buffer are recommended. Sediment traps or retention basins, constructed wetlands, terraces, and on farm water and nutrient management can reduce P impacts to waterways (NRCS 2005).

Pesticides

Pesticides are a broad range of chemicals used for the control of undesirable plants, animals, insects and fungi. These include herbicides, insecticides, fungicides, and rodenticides. Runoff from pesticides is estimated to be 1 to 5% of the amount applied (Arora et al. 2003). Retention of pesticides in the soil depends on its ability to adsorb to soil particles. Pesticides losses from agricultural fields are mainly due to timing of application, slope, and tillage practices (Arora et al. 2003; Boyd 2003).

Reasons for concern

Excess runoff can result in pesticide contamination of drinking water and aquatic habitats. Toxic effects can be lethal or sublethal. Sublethal doses can cause impairments such as slowed reflexes, impaired learning behavior, lower reproductive success (Mason 2002) and loss of biodiversity (Harris and Forster 1997). Many pesticides can concentrate in animal fats causing death or sterility. Concentrations of DDT and DDE have been found in human breast milk (Mason 2002), although these rates are declining in Japan and the U.S.

How buffers affect pesticides

Pesticides may be weakly or strongly adsorbed to soil particles (Arora et al 2003; Boyd 2003) and losses from water transport can be rapid (Harris and Forster 1997) with peak concentrations occurring soon after application. The mechanisms of pesticide transport, however, are not well understood (Harris and Forster 1997; Wenger 1999). Pesticides may enter the stream channel either through surface or subsurface flow, and particle transport. Saturation of soil or compaction promotes excess pesticide movement in surface flow (Harris and Forster 1997).

Riparian buffers can reduce the amount of pesticide runoff from cropland by adsorption, infiltration, and microbial breakdown (Arora et al. 1997; Barfield et al. 1998; Lowrance et al. 1998; Arora et al. 2003). Research has shown that the area ratio, or the ratio of the contributing surface runoff area to the filter strip area, has a significant effect on runoff infiltration and sediment, nutrient and pesticide retention rate of vegetated filter strips (Arora et al. 2003; Boyd et al. 2003). Arora et al. (2003) found that buffers reduced the concentrations of two herbicides but not an insecticide in outflow. All three pesticides, however, were more highly retained in the 15:1 ratio plots than in the 30:1 plots. They concluded that herbicide reduction was through infiltration; while the insecticide was reduced through adsorption and that the 30:1 plot had higher runoff rates. Boyd et al. (2003) also found that infiltration and adsorption played a key role in chemical retention. They found that sediment, and therefore insecticide reduction, was higher in the 15:1 ratio plots compared with 45:1 plots due to adsorbtion while there was no difference for the herbicides. Higher amounts of pesticides are found with increasing concentration and flow rate (Kloppel et al. 1997). Buffer widths of 8 to 20m were shown to decrease pesticides by up to 100% in some cases with trapping efficiency increasing with width (Patty et al. 1997; Verdilis et al. 2002) (Matrix B).

Pathogens

Pathogens include a variety of organisms such as bacteria, viruses, protozoa, and helminths (parasitic worms). Of particular concern in the Intermountain West are those organisms associated with livestock. Concentrated animal feeding operations may contribute substantial amounts of pathenogenic contaminants to waterways. Direct access by livestock and wildlife to streams and rivers can also introduce these contaminants to waterways. Spreading contaminated manure and sewage wastewater though irrigation increases the risk of spreading disease in surface water (Mason 2002).

Reasons for concern

Worldwide, waterborne pathogens kill 25 million people per year and disable millions more. Children are the most frequent victims through dehydration caused by diarrhea. Birds, livestock, and other animals often transmit these diseases (Mason 2002). In Egypt and other parts of Africa, the removal of natural flood regimes has led to a buildup of a permanent population of snail hosts of *Schistosoma spp.*, a parasitic worm causing anemia and reduced immunity to other diseases.

In the U.S., the recommended standard for the pathogen fecal coliforms for direct human contact with water is 200 colonies forming units (CFU) per 100 ml (Coyne et al. 1998; Wenger 1999); however, for drinking water the EPA (2005) has set a goal of zero. No more than 5% of the samples in the public water supply taken in each month may have coliforms.

How buffers affect pathogens

Trapping efficiencies for pathogens in grass buffers tend to be high, amounts of bacteria in grass buffers were often found to be significantly greater than the standard of 200 CFU per 100ml (Chaubey 1994; Coyne et al. 1998). Entry et al. (2000a) found no decline in total and fecal coliforms in applied wastewater through an 8m (26.25ft) buffer regardless of season or vegetation type. They did, however, see a decrease in total and fecal coliforms with depth to 30cm (11.8in) and over time. Ninety to 120 days following application, concentrations of fecal coliforms in treated filter strips were similar to those in non treated riparian filter strips (Entry et al. 2000b). Lim et al. (1998), however, found that a 6.1m (20.01ft) tall fescue (*Festuca arundinaceae*) buffer removed 100% of the fecal coliforms but Young et al. (1980) concluded that a 36m (118.1ft) buffer would be required to reduce total and fecal coliforms to below 1,000 organisms per 100ml (Matrix D). Most of the studies of coliforms looked at the effects of grass buffers. It is unclear whether a multi-species buffer would have greater total coliform removal capacity.

Escherichia coli survival in water tends to be about 24 hours and 2 to 4 hours in soil and sediments. There is evidence, however, that E. coli can survive and proliferate in warm, moist soil conditions with appropriate nutrient concentrations (Source Molecular 2004). Although this is more common in tropical areas, it occurs in temperate riparian areas as well (Byappanahalli et al. 2003; Whitman et al. 2003). Appropriate riparian buffer widths may help to slow down transport of certain pathogens. If bacteria reach areas where conditions are appropriate for proliferation, such as moist riparian zones, total elimination may not be possible by using buffers alone. Using BMPs for manure and limiting livestock access to streams would be more appropriate in reducing concentrations to the buffer.

Studies investigating concentrations of *Cryptosporidium parvum,* a microbe transmitted from livestock to humans, found that slope, soil type, and rainfall intensity affected infiltration rates (Atwill et al. 2002; Tate et al. 2004; Trask et al. 2004). Clay soils were less effective in removing of oocysts from the buffer but greater amounts were found in subsurface flow in sandy and loam soils (Atwill et al. 2002). As with *E. coli*, it is unclear how effective grass buffers would be since studies of *C. parvum* were conducted only in 1m (3.3') trial boxes with simulated rainfall with or without grass (Atwill et al 2004; Tate et al. 2004; Trask et al. 2004).

Dissolved Contaminants

Nitrogen (N)

Nitrogen is an important nutrient for plant and animal growth and function. Nitrogen is also an important component of amino acids, the building blocks of proteins, and plays a role in plant carbohydrate use and root development. Nitrogen fertilizer application can increase plant growth and therefore; it is widely used in agricultural production (Brady and Weil 2000).

Nitrogen is available in organic and inorganic forms. Most of the N in soil is in organic forms associated with humus. Inorganic nitrogen, found mainly in fertilizer nitrogen, is highly soluble therefore readily leached. Nitrate (NO_3^-) and ammonium (NH_4^+) forms of nitrogen are readily taken up by plants but available typically in relatively small amounts (Brady and Weil 2000).

Reasons for concern

The largest sources of N to streams are through N fertilizer and concentrated livestock feedlots and manure application to lands adjacent to riparian areas. Up to 90% of hog waste can volatilize as ammonia (NH^3) (Phelps 1997). Atmospheric deposition and septic systems are also significant sources of NO_3^-. Approximately 25% of the total Chesapeake Bay N load comes from atmospheric deposition (NOAA 2005). Some of the excess NO_3^- has been implicated in methaemoglobinaemia in infants less than six months old where ingestion of NO_3^- above 100 mg per L of water results in reduction of red blood cells to carry oxygen and is often fatal. The standard for NO_3^- in drinking water in the United States is 10 mg per L NO_3^--N (EPA 2004). Also, NH^3 is directly toxic to aquatic life with susceptibility related to body size, age or sex (Mason 2002).

Nitrogen can also contribute to eutrophication (Mason 2002; Zheng et al. 2004). Increased algal blooms create low oxygen conditions due to decay of organic material and reduce fish and plant diversity (Hart et al. 2004). Application of N over time can cause microbial sinks to become saturated and thus less functional (Hanson et al. 1994), releasing large quantities of nitrogen oxide (NO) gases to the atmosphere (Burt et al. 1999; Hefting et al 2003). Although less of an issue in the West, a pH of less than 5 will inhibit denitrification and cause increased release of NO gas (Brady and Weil 2000) causing acid rain (Mason 2002).

How buffers influence N dynamics
Removal through uptake or leaching of NO_3^- in riparian areas has been investigated more than any other potential pollutant (Gilliam 1994). Most of the research on nitrogen dynamics prior to 1980 was concerned with surface flow (Correll 1997). Interest in subsurface processes concerning nitrogen began in the early 1980s with studies showing reductions in nitrogen concentrations of 90% through forest buffers on the Atlantic Coastal Plain (Gilliam et al. 1997).

Buffers influence N dynamics through two major pathways; plant uptake and denitrification by soil microbes in the riparian zone (Gilliam et al 1997; Burt et al. 1999; Lamontagne 2001). Denitrification is a natural process that occurs in the soil where microbes reduce NO_3^- to dinitrogen (N^2) gas which is then released to the atmosphere. Denitrification requires a source of N, appropriate microbial population, a soluble carbon source for metabolic function of microbes, soil moisture, and low oxygen conditions (Hanson et al. 1994). Optimum soil temperatures for denitrification range between 25 and 35ºC (Brady and Weil 2000). Although carbon is generally plentiful in the upper soil profile, soil microbes may only be able to carry out denitrification during times of high soil moisture, such as spring and early summer (Burt et al. 1999). Also, heterogeneous sediments and soils may affect subsurface flow paths and residence time; therefore, N may bypass the riparian area and proceed to the stream channel (Karr et al. 2000). The importance of understanding site hydrology is critical for this nutrient (Hill 1996; Burt et al. 1999; NRC 2002).

The role of plant uptake of N in riparian systems has not been extensively investigated (Hill 1996). In riparian areas with inadequate conditions for denitrification, plant uptake may play a greater role in removal. Lowrance et al. (1984) found that nutrient uptake by trees in a riparian zone acted as short to long-term sinks, preventing nutrients from entering the stream. Periodic removal of vegetation was therefore hypothesized to maintain net uptake of nutrients in the riparian zone. Peterjohn and Correll (1984) found that up to 80% of nitrogen in a deciduous forest was returned to the riparian system as litter (Peterjohn and Correll 1984), where much of this was mineralized by soil microbes. Sites with leguminous plants may show no vegetation uptake of N because of N fixation and; therefore may be more dependent on the role of denitrification in the soil (Tate et al. 2000).

Nitrogen retention through plant removal and denitrification depends on many factors. Site characteristics, particularly hydrologic features such as shallow aquifers with confining layers, allow groundwater to flow through the root zone and reduce NO_3^- through denitrification (Wenger 1999; Lamontagne et al. 2001). Most studies found significant decreases of nitrogen with increasing buffer width (Matrix E). Most of the total NO_3^- reduction occurred 10 to 35m (32.8 to 114.8 feet) into the buffer (Peterjohn and Correll 1984; Jacobs and Gilliam 1985; Lowrance, Richard 1992; Haycock and Pinay 1993; Jordan et al. 1993; Osbourne and Kovacic 1993; Pinay et al.1993; Chaubey et al. 1994; Patty et al. 1997; Hubbard et al. 1998; Lim et al 1998; Mendez et al. 1999; Lee et al. 2000; Lowrance et al. 2000; Spruill, Timothy 2000; Dukes et al 2002; Bedard-Haughn et al. 2004).

Nitrogen in soils are generally not sufficient for optimum crop production; therefore it is added in fertilizer form. Since N is highly soluble and mobile, it is easily leached into groundwater. (NRCS 2005). Most N losses into streams travel in groundwater though subsurface flow and deeper baseflows (NRCS 2005). Although up to 50% of N applied as fertilizer is lost to groundwater (Mason 2002), NH_4^+ in soil organic matter adsorbed to clay particles is lost in overland flow from erosion. Slope increases flow rate; therefore increasing surface roughness can play a role in reducing transport (Kleinschmidt 1999; Johnson and Buffler 2005; NRCS 2005).

Soil properties such as infiltration rate and timing of rainfall or irrigation affects losses of N (Brady and Weil 2000). Soils with low infilitration rates will have increased rates of N losses through overland flow (NRCS 2005). Nitrate moves slowly through the unsaturated zone in the soil. Because of this, retention in soil can remain for long periods of time.

In general, buffers tended to reduce NO_3^- concentrations with increasing width (Dukes et al. 1993; Patty et al. 1997; Hubbard et al. 1998;Lee et al. 2000; Bedard-Haughn et al. 2004). Significant reductions were seen in the first 5 to 10m of the buffer (Mendez et al. 1999; Lowrance 2000). Schmitt et al. (2000) found that sediment bound N was reduced more effectively in wider buffers than dissolved N but others found no differences (Vanderholm and Dickey 1978; Peterjohn and Correll 1984; Lee et al. 2000).

Both grass, wooded and combination buffers were effective in reducing N concentrations. (Lowrance et al. 1984; Osbourne and Kovacic 1993; Castelle et al. 1994; Lee et al. 2000; Dukes et al. 2002). Buffers, however, will have no effect if NO_3^- is bypassing the root zone in groundwater (Chaubey ey al. 1995; Karr et al. 2001; Wigington et al. 2003).

Vegetation type and hydrologic and geological considerations of the site should be taken into consideration in order to appropriately assess conditions appropriate for removal of dissolved nutrients.

Dissolved Phosphorus (P)
About 80 to 90% of P in the soil is available very slowly. Labile or slowly available forms make up about 10 to 20% of the soil P with less than 1% readily available. Dissolved P is found in several forms and include the inorganic mono and dicalcium phosphate although in extremely alkaline soils, calcium causes P to become insoluble. Phosphorus fixation tends to occur more readily in clay soils due to their high surface area. (Brady and Weil 2000). Organic forms of P can be mineralized from decaying plant material or manure to provide soluble forms of P for plant uptake. Desorption of P from soil and vegetation can be transported through rain or snowmelt (Uusi-Kamppa 1997).

Reasons for Concern
Up to 45% of the phosphorus component entering riparian areas in runoff is in dissolved form (Uusi-Kamppa et al. 1997; Fleming and Cox 2001) Dissolved P is initiated by desorption from soil or plant particles. Adsorption sites on soil particles may become saturated causing an excess concentration of dissolved P in runoff. Cold soil temperatures reduce plant uptake; therefore P runoff may be higher in spring (Uusi-Kamppa et al. 1997; NRCS 2005). Orthophosphate (PO_4-P) is the main source of dissolved inorganic P in surface runoff (Uusi-Kamppa et al. 1997).

How Buffers Influence P Dynamics
Riparian buffers are less effective in reducing the amount of dissolved P than sediment bound P (Gilliam 1994). Several studies (Matrix C) show that a significant amount of PO_4-P was removed in 9 to 21m grass buffers (Young et al. 1980; Lim et al 1995; Patty et al. 1997; Chaubey et al. 2000) although other studies showed that PO_4-P removal was less or not effective (Daniels and Gilliam 1996; Snyder et al. 1998; Schmitt et al. 1999; Lee et al 2000) or even increased in the buffer (Peterjohn and Correll 1984) (Matrix C).

Although the EPA (2005) has not set a standard for P, the state of Utah recognizes 0.05 mg per L as the limit (EPA Utah 2005). As with particulate P, BMPs to reduce P before it enters the buffer are recommended. Removal of biomass in the buffer may also help reduce the amount of P taken up in vegetation (Uusi-Kamppa 1997).

Buffer Design and Guidelines

The National Resource Conservation Service (NRCS 2005) defines conservation buffers as **"small areas or strips of land in permanent vegetation, designed to intercept pollutants and manage other environmental concerns. Buffers include: riparian buffers, filter strips, grassed waterways, shelterbelts, windbreaks, living snow fences, contour grass strips, cross-wind trap strips, shallow water areas for wildlife, field borders, alley cropping, herbaceous wind barriers, and vegetative barriers"** (NRCS 2005).

The Intermountain West is unique since most streams originate on public lands at higher elevations (Fry et al. 1994; Cushing and Allan 2001). Water quality of higher order valley streams is therefore dependent on management by federal agencies making placement and design of riparian buffers in the watershed critical for protecting water quality downstream (Fisher et al. 2000; Fischer and Fischenich 2000).

Several buffer designs for watler quality developed by federal agencies are currently in use. These designs employ various combinations of herbaceous plants, grasses, shrubs, and trees. The design most widely used is the USDA Forest Service's three zone design (Welsch 1991). These guidelines, however, were developed primarily for the eastern United States. The Leopold Center for Sustainable Agriculture at Iowa State University developed the multi-species buffer (MSRBS) for small mid-western streams (Schultz et al. 1994). The MSRBS buffer system is specifically designed for use in the Midwest; however, it is designed so that the specific width planting zones can be varied depending on landowner objectives. The MSRBS design also includes constructed wetlands for amelioration of agricultural chemicals. This design, although slightly more flexible, is another variation on the USDA three zone design and may not be applicable to the Intermountain West. The specified widths for these zones are based on "best professional judgment" or socio-political concerns (Dillaha and Inamdar 1997; Fischer et al. 2000; Fischer and Fischenich 2000)

Current riparian buffer design guidelines for use in the western United States were developed primarily by states with substantial forestry interests on fish bearing streams (Belt and O'Laughlin 1994). Oregon, Washington, and California require variable width buffers with minimum and maximum width ranges depending on variables such as slope, adjacent land use, and stream width. This gives consideration to the variation in plant density found in these states (Belt et al. 1992). These states also require use of percent canopy cover and vegetation structure to protect stream temperature (Belt and O'Laughlin 1994). Instead of specific width zones used in the east and Midwest, western riparian buffer design guidelines tend to be more flexible and use site attributes as key determinants of buffer design and subsequent success in forested landscapes.

Oregon has a specific set of guidelines for certain circumstances that restrict harvesting to within 10 to 20 feet (3 to 6m) of the high water mark (Blinn and Kilgore 2001) while Idaho has a set minimum width of 75 feet (22.9m) for all fish bearing streams and a minimum 5 foot (1.5m) buffer for non-fish bearing streams. State developed guidelines were reviewed by Blinn and Kilgore (2001). The most common recommendations were a 50 foot (15.2m) fixed width buffer on both sides of the stream with 50% to 75% canopy crown closure. They found that most guidelines include: a minimum width from the high water mark of the stream, a minimum amount of residual trees following harvest, and other guidelines considering land use practices within the riparian management zone. Of 16 western states, buffer width requirements range from 40 to 200 feet (12.2 to 60m) for perennial and intermittent streams, although none of the western states had site specific width requirements (Blinn and Kilgore 2001).

Although fixed width buffers are simple and relatively easy to establish and regulate (Fisher et al. 2000), variable width buffers allow for a variety of options and ecological functions. Although more complex, they have the ability to provide more effective protection due to better response to local site conditions (Belt and O'Laughlin 1994; Blinn and Kilgore 2001). For instance, proximity to and types of adjacent land uses should be considered when designing buffers (Fischer et al. 2000).

Guidelines for revegetation of riparian areas in the Intermountain West were developed by the Plant Materials Center at Aberdeen, Idaho (Carlson et al. 1995; Hoag et al. 2001). Although no specific width designations are given, the authors provide valuable recommendations for planting in the appropriate zone depending on the stream type and hydrology. These planting zones are based on native riparian areas and are used as a guide for appropriate planting for restoration. There are five basic zones delineated for appropriate plant community types: the toe zone, bank zone, overbank zone, transitional zone, and the upland zone (Hoag et al. 2001). Design criteria are based on geomorphology, stream types and size, plant community types, velocity, sinuosity, bank slope, uniformity, and stratification of stream bank materials (Carlson et al. 1995). The goal is to establish appropriate, dense, native vegetation to stabilize stream banks. These restoration recommendations would work well within an appropriate set of riparian buffer design guidelines.

Recommended buffer widths based on a review of the pertinent literature lead to recommendations based on a range of widths. Since no studies were found comparing buffer widths in the Intermountain West, extrapolations from existing literature combined with differences between riparian areas in the eastern and western U.S. were made. The buffer widths recommended in Table 6 are based mainly on studies conducted in the eastern U.S. with modifications for arid landscape conditions.

Table 6. Summary of buffer width recommendations required for removal of selected contaminants.

Contaminant	Width*	Effect
Nitrogen mostly soluble	20 to >40m may be narrower under ideal site conditions	Nitrogen trapping is dependent on vegetative uptake and transformations in the soil, and is dependent on soil moisture. Removal increases with buffer width and is greater in woody vegetation. Ground and surface water hydrology plays an important role in N removal
Sediment particulate	3 to >10m	Sediment trapping efficiency declines from 3 to 6m into buffers, regardless of slope. Grass buffers are more effective than forest buffers for removal although high flows and channelization will counter any beneficial effects
Phosphorus particulate and dissolved	>20m	Sediment bound P follows similar trends as sediment, however, dissolved organic and inorganic P is more difficult to retain. A combination of grass and forest buffers are most efficient for trapping both types of P
Pathogens associated with sediment	3 to >6m depending on pathogen load, antecedent conditions, slope, and soil conditions	Most pathogens can be removed from short buffers. Increasing slope may increase surface flow. Survivability of organisms may affect how long a buffer needs to be to slow movement

Pesticides particulates associated with sediment	>9m depending on antecedent conditions, adsorption, and chemical type	Pesticides are adsorbed to soil particles with varying effectiveness, Other pesticides can be infiltrated. Trapping efficiency increases with increased infiltration. Trapping widths are variable with grass more effective in removing most pesticides

*based on 90% removal rate

Summary

Over 120 documents including scientific literature, literature reviews, books, technical notes, and reports and proceedings were reviewed and summarized. The American Water Resources Association 2004 Conference was also a valuable source of information.

Most of the research on riparian buffers was conducted in the East or on forested streams in the Pacific Northwest or other areas where logging activity was the predominant land use. Belt et al. (1992) reviewed buffer width requirements for Idaho, Washington, California, and Oregon and recommended design guidelines for forested areas in those states. These guidelines apply to low order, high elevation, headwater streams in forested landscapes. While protecting headwater streams is critical, most streams and rivers found in valleys of the Intermountain West (the study area) are higher order and run through agricultural and rangelands. Typically, these higher order streams have narrow or no riparian buffers.

The literature reviewed strongly suggests that buffer width is the most important factor influencing removal of contaminants (Davies and Nelson 1999; Gilliam 1997; Jones 2001; Hook 2003). A range of buffer variables including attributes related to topography, soils, hydrology, and vegetation that affect buffer function and thus width was presented in the literature. Criteria used to select riparian attributes for determining buffer width in this study include:

- strong attribute correlation with buffer function in the Intermountain West
- readily available data or easily measurable
- minimal opportunity for subjective interpretation
- easily replicated

Attributes

Buffer attributes selected based on the criteria above include slope, soil infiltration capacity, surface roughness, surface water features, sand and gravel aquifers, seeps and springs, floodplains, wetlands, and stream bank condition. Many of these attributes are common to other buffer planning methods as noted in Kleinschmidt (1999). Slope, soil, and surface roughness have the greatest effect on buffer functions for water quality (Buffler 2005).

Primary Attributes

The literature review of riparian buffer attributes in the study area and communications with regional resource experts suggests that, in general, riparian buffers in the Intermountain West should be wider than those recommended for other regions of the United States. Reasons for increased width based on an assessment of regional primary and secondary attributes include the following:

- Slope gradient - streambank slopes on many high order streams in the study area are steeper than those found in other regions often a result of channel incisions. Overland flow is accelerated and infiltration reduced; thus wider buffers are required to attenuate contaminants.

- Soil infiltration - in general, in arid landscape soils are shallow, high in clay content and often saline. Infiltration rates are low and overland flow high necessitating wider buffers.

- Surface roughness - in the study area, riparian areas are often narrow fringes, plant density and percent ground cover are highly variable but generally lower than in other regions. Uplands adjacent to the buffer, plant density and litter are also low. The result is reduced surface roughness and higher overland flow in the buffer which suggests that wider buffers are required.

Secondary Attributes

- Seeps and springs - springs and seeps, often a product of irrigation, are common in the study area. Unless buffered, they become a conduit for contaminants. Buffers should be wider to include seeps and springs.

- Sand and gravel aquifers - sand and gravel aquifers have high infiltration rates and can become sub-surface conduits for contaminants particularly nitrogen and disssolved phosphorus. Buffers need to be widened to include these attributes.

- Floodplains and wetlands - wide floodplains and associated wetlands are relatively common on higher order, lower elevation streams in the study area (with some channelized exceptions). To accomodate these features floodplains and associated wetlands are considered part of the stream being buffered. Buffer widths are calculated from the landward edge of these features.

To conclude this discussion of buffer width, Baker et al. (2003) noted that in the Intermountain West, sparse vegetation, shallow soils, lower infiltration rates and short intense rainfall events may necessitate wider buffers.

Planning Protocol

Several buffer planning protocols were reviewed. They varied from protocols based on visual estimates to those that were data intense, required significant inputs of field collected data and utilized computer modeling. Of the protocols reviewed, the protocol developed by Klienschmidt Associates Method to Determine Optimal Buffer Widths for Atlantic Salmon Habitat Protection (1999) best matched the goals of the RB Handbook "develop a protocol for determining appropriate riparian buffer widths and guidelines on agricultural lands in the Intermountain West. "The protocol combines visual estimates, readily available resource data, easily measurable attributes and requires field verification of all mapped information. The protocol incorporated the buffer attributes noted above and utilized sampling plots (buffer measuring units) that could be adapted to western landscape characteristics. The protocol emphasized keys and tables that expedite data collection, recording and calculations, and facilitate replication. Buffer attributes keys and tables in the Kleinschmidt protocol were easily modified to accomodate unique Intermountain West landscape attributes. Lastly, the Kleinschmidt protocol adopted by the state of Maine to protect spawning habitat for the endangered Atlantic salmon was thoroughly scrutinized and approved by resource experts and regulatory agencies.

Outcomes from the protocol include a mapped variable width riparian buffer for water quality and land use zones with management specifications. In the Intermountain West permitted uses within the buffer and management will be key to the long-term effectiveness of riparian buffers.

The importance of BMPs in the buffer zone and on adjacent lands cannot be overstated. In many cases, buffers alone may not be sufficient to reduce or eliminate contaminants. Contaminants, most importantly NO_3^-, can bypass buffer zones. Constructed wetlands such as those used in the Leopold Center for Sustainable Agriculture's 3 Zone buffer system are specifically designed to deal with agricultural chemicals (Schultz et al. 1994).

Ecosystems change over time; therefore monitoring will become necessary and adaptive management a likely possibility.

Photo credit: Susan Buffler

Bear River, northern Utah.

MATRIX A - SEDIMENT

AUTHORS	YEAR	STATE	BUFFER WIDTH AND TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
Applebloom et al.	2002	NC	90cm grass strip	NA	Compared with no grass strip, a 90cm strip next to a road, reduced sediment loss by an average of 56%.
Barfield et al.	1998	KY	4.6m bluegrass/fescue 9.1m 13.7m	9%	Conventional and no-till plots in a **karst** watershed (well structured soils with high infiltration rates) No-till plots were more effective in trapping sediment. Sediment retention increased with increasing buffer width Most of the sediment was trapped in first 4.57m in the no-till plots. Trapping efficiencies were over 95%
Barden et al.	2003	KS	12.2m small trees+native grass 12.2m small trees+fallow 12.2m fallow (7 yrs) to allow for succession	not specified	**Silty clay loam**/natural rainfall+simulation No significant difference in vegetation types for total suspended solids with natural rainfall but ranged from 40-75% reduction. Simulated rainfall reduced TSS by 90%. Data highly variable under natural rainfall conditions
Chaubey et al.	1994	AR	no buffer 3m grass 6m grass 9m grass 15m grass 21m grass	3%	**Silt loam** soils - swine manure applied at 200 N kg per ha Effectiveness in reducing total suspended solids did not extend significantly beyond 3m
Chaubey et al.	1995	AR	no buffer 3.1m uncultivated 6.1m grass 9.2m grass 15.2m grass 21.4m grass	3%	Uncultivated areas ammended with poultry litter Mass transport of total suspended solids was reduced by 35%. Effectiveness in reducing mass transport of total suspended solids did not extend significantly beyond 3m

Daniels and Gilliam	1996	NC	1. fescue strip across lane into groundcover or mixed hardwoods and pines 2. narrow fescue to grass waterway through mixed weeds and small shrubs to larger trees	4-15%	Two locations #1 **Sandy loam** to **clay loam** surface horizons #2. **Silt loam / silty clay** 1 and 2 ephemeral and intermittent streams Looked at vegetation structure; cultivated fields; natural rainfall Runoff reduced by 50 to 80%. Total sediment reduced by 80% High flows overwhelmed filters
Dosskey et al.	2002	NE	9-35m trees/grass (four farms)	1-9%	Potential sediment removal could be up to 99%, but, due to varying topography and uneven distribution, concentrated flow reduced effective removal to <43%
Fasching and Bauder	2001	MT	12.2m grass / small grains	4%	Looked at antecedent soil conditions on deep **well drained soils** with high water holding capacity & low permeability. (50yr 24hr simulated rainfall event) sediment concentration in prewetted soils was reduced by 68%. In dry soil concentration reduced by 85%
Fiener, P. and K. Aueswald	2003	Germany	variable 10-59m mowed grass and no maintenance 2 watersheds	3.6-5%	Runoff was reduced 90% and 10% for the 2 watersheds while sediment delivery was reduced 97 and 77%, respectively
Hook	2003	MT	6m riparian pasture - sedge wetland, rush transition, bunchgrass upland	2-20%	Looked at buffer structure on colluvial and alluvial slopes 94-99% sediment retention in 6m buffer regardless of vegetation type or slope. Varying rates for other combinations. Sediment retention was not affected by stubble height
Jin and Römkens	2001	sim.	6m simulated filter strip ploypropylene bristles	4 and 6%	Trapping efficiency increased with increasing density but decreased with increasing slope. Over 80% of the deposition occurred in the top 50% of the filter strip on research plots and bare plowed soils

Lee, Kye-Han et al.	2000	IA	no buffer 7.1m switchgrass 16.3m switchgrass-woody	5% (crop) 8% (buffer)	**Cropland = loam; buffer = silty clay loam** Simulated rainfall on bare cropland. 7.1m switchgrass buffer removed 70% of the incoming sediment and >98% sand, >71% silt; >15% clay 16.3m switchgrass-woody buffer removed >92% of the sediment and >98% sand; >93% silt; and >52% clay
Lim et al.	1998	KY	no buffer 6.1m tall fescue pasture 12.2m tall fescue pasture 18.3m tall fescue pasture	3%	**Silt loam soils** / simulated rainfall Total suspended solids removed in first 6.1m No significant reductions beyond 6.1m
Mendez et al.	1999	VA	no buffer 4.3m grass 8.5m grass	ns	Sediment deposited in the first few meters of the buffer strip. Sediment concentration was reduced by 83% (4.3m) and 87% (8.5m)
Nerbonne and Vondracek		MN	ungrazed grass 32m±16m grazed grass 74±15m wooded 94±14m		Looked at upland & riparian land use,climate,vegetation structure. Percent fines and embeddedness decreased with increasing buffer width. Fines were lower in grassbuffer sites even though they were narrower. Wooded and grazed buffers of <150m had <50% fines in the streambed, however, only grass buffers had had <50% fines in streambed when buffer was <100m
Patty et al.	1997	France	no buffer 6m grass 12m grass 18m grass	7, 10, 15%	3 sites with **silt loam** soils ranging from 2 to 7% organic matter. Plots planted with ryegrass next to field cultivated to winter wheat. Runoff volume was reduced from 43% to 99.9% and suspended solids were reduced by 87% to 100%.
Robinson et al.	1996	IA	18.3m grass	7, 12%	Initial 3m of the filter strip removed >70% of the sediment. 9.1m of the buffer removed 85%

Schmitt et al.	1999	NE	7.5 and 15m for all treatments 25 year grass plots mixed grass (2 yr) 50% grass 50% trees + shrubs (2 yr) grain sorghum (2 yr)	6 to 7%	76-93% reduction of sediment in simulated field runoff **Silty clay loam** to **sandy loam**; simulated rainfall Significant width effect on volume and concentration of all contaminants with most reduction within the first 7.5m
Sheridan et al.	1999	GA	Zone 1 - 10m hardwoods Zone 2 - 45-55m managed forest Zone 3 - 8m grass	3.5%	**Loamy sand** soils - three forest treatments (mature, clearcut and selectively thinned Zone 2) Runoff was reduced 56% to 72% in the grass buffer strip before it entered the forest No significant differenced were observed among Zone 2 treatments. 63% of the sediment reduction occurred in the grass filter strip
Syversen et al.	2001	Norway	5m mowed grass and weeds	14%	Average particle retention 65%. Most of the retention was in the top part of the buffer
Tate et al.	2000	CA	no buffer 10m pasture buffer	rolling foothills	Sprinkler and flood irrigated pasture composed of 40% clovers and 60% grass Pastures grazed from June to October Water use efficiency was low and distinct temporal runoff patterns were observed 15% to 69% of the irrigation water became runoff The authors found more runoff per unit area was produced from pastures with buffers Total suspended solids (TSS) load was not reduced on sprinkler irrigated pastures TSS concentration was reduced for both irrigation treatments and TSS load was reduced under flood irrigation

AUTHORS	YEAR	STATE	BUFFER WIDTH AND TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
REVIEWS					
studies showing removal of a substantial portion of sediments in overland flow					
in Castelle et al.	1994				
Broderson	1973		61m		Controlled sedimentation even on steep slopes
Ghaffarzadeh et al.	1992		0-18.3m grass	7&12%	No slope differences in performance beyond 9.1m (85% removal)
Horner and Mar	1982		61m grassy swales		
					Removed 80% suspended solids
Lynch	1985		30m between logging and wetland/ streams		Removed 75 to 80% of sediment
Schellinger and Clausen	1992		22.9m		Removed only 33% of suspended solids
Wong and McCuen	1982		equation determining buffer width		If removal needs to increase from 90 to 95% on a 2% slope, buffer width needs to double
in Wenger, Seth	1999				(% removal of total suspended solids)
Clinnick	1985		30m		Exhibited similar channel stability & biological diversity as unlogged streams
Coyne et al.	1995		9m grass		
					99% sediment trapped (poultry waste added to grass buffers). Looked at one simulated rainfall event
Davies and Nelson	1994		30m		Logged forests - effects dependent on buffer width and not on slope, erodability, or time
Desbonnet et al.	1994		25m		Most efficient width for sediment removal
(based on a review)			60m		Most efficient width for total suspended solids
Dillaha et al.	1988		4.6m orchardgrass		On a simultated feedlot a 81% reduction of TSS
			9.1m orchardgrass		91% for 9.1m buffer
Dillaha et al.	1989		4.6m orchardgrass		Below bare fertilized cropland there was a 70% sediment
			9.1m orchardgrass		reduction. 84% for a 9.1m buffer
Gilliam	1994		narrow (width not stated)		Trapped 90% of sediment
Maguette et al.	1989		4.6m	3.5%	66% sediment reduction (liquid poultry waste or liquid N)
			9.1m	3.5%	82% sediment reduction (liquid poultry waste or liquid N)
Peterjohn and Corell	1984		19m	5%	90% removal of TSS
Peterjohn and Correll	1984		50m	5%	94% (agricultural catchment - 90% trapped in first 19m)
Rabeni and Smale	1996				Buffer width may not be as important as other qualitative characteristics such as sheet flow

Young et al.	1980		21.3m 27.4m	4% 4%	75-81% removal of TSS 93% average removal of TSS
in Fischer and Fischenich	2000				
Horner and Mar	1982		≥61m grass filter strip/vegetated buffer		80% of sediment in stormwater removed
Ghaffarzadeh et al.	1992		≥9m grass filter strip	7&12%	Removed 85% of sediment
Lynch et al.	1985		≥30m		Sediment removed 75 to 80% of sediment from a buffer bewteen logging activity and stream
Dillaha et al.	1989		≥9m vegetated filter strip		Removed an average of 84% suspended solids
in Fischer and Fischenich (White Paper)	2004		2,5,10,15m grass filter strips 4.6m and 9.1m		Removal of sediment averaged 80% to 95% Sediment reduced by 87% in 9.1m stirps and 71% in 4.6m stips
Gharabaghi et al.	2000				
Mickelson et al.	2003				

MATRIX B - PESTICIDES

AUTHORS	DATE	STATE	BUFFER WIDTH AND TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
Arora et al.	1997	IA	20.1m	3%	**Silty clay loam** soils. Natural rainfall Looked at two drainage to buffer area ratios Retention was dependent on antecedent conditons Atrazine: Retention in buffer ranged from 11-100% Metalochlor: Retention ranged from 16-100% Cyanazine: Retention ranged from 8-100%
Arora et al.	2003	IA	20.1m		Looked at two drainage to buffer area ratios or inflow rates (15:1 and 30:1) Concentrations of herbicides in runoff outflow were less than in inflow but greater for chlorpyrifos Atrizine: 15:1 treatment retained 52.5%; 30:1 treatment retained 46.8% Metalochlor: 15:1 treatment retained 54.4%; 30:1 treatment retained 48.1% Chlorpyrifos (insecticide): 15:1 treatment retained 83.1%; 30:1 treatment retained 76.9% No significant differences were found for the three treatment Most of the herbicide retention was through infiltration while insecticide retention was through adsorption
Barfield et al.	1998	KY	4.6m bluegrass/fescue 9.1m 13.7m	9%	Conventional and no-till plots in a **karst** watershed (well structured soils with high infiltration rates). Trapping efficiency increased with increased infiltration The 9.14m buffer trapped an average of 97% of the atrizine Effeciency declined slightly for the wider buffer at 94%

Boyd et al.	2003	IA	4.6m grass 9.1m grass	3.50% (source area) 2% filter	**Clay loam**; Looked at two drainage to buffer area ratios or inflow rates (15:1 and 45:1) Infiltration and adsorption played a large role in chemical retention. Sediment reduction was higher in the 15:1 plots than in 45:1 plots for Chlorpyrifos Chlorpyrifos was not detectable in runoff Atrizine and metalochlor; no significant reduction between the 15:1 and 45:1 plots
Kloppel et al.	1997	Germany	10m grass 15m grass 20m grass	field 8% buffer 5%	Field study; titicale with grass filter; silt loam soil Looked at channelized flow and sheet flow Three flow rates. Three herbicides, erbuthylazin, isoproturon, and dichlorprop-p were applied. Samples were taken at 10, 15, and 20m into the buffer Runoff was reduced from 46 to 92% overall for all runoff rates and buffer lengths although no clear trend was observed. Higher amounts of all herbicides were found with increasing flow rate and concentration applied. Efficiency of herbicide retention was due to infiltration.
Krutz et al.	2003	TX	3m buffalograss	2%	Atrazine and atrazine metabolites were measured on **saturated clay soil** (60 minute simulation) Retention was greater for atrazine (22%) than atrazine metabolites (19%)
Lowrance et al.	1998	GA	8m grass 40-55m slash pine 10m hardwoods		**Loamy sand**; natural precipitation; upland continuous corn crop. Two treatments in the slash pine buffer; clear cut and thinned Alachlor and atrazine reduction was greatest in grass buffer. Most of the herbicide transport occurred before June 30. Reduction from 34 to <0.05µg per L of both herbicides at hardwood zone

Mersie et al.	1999	VA	bare switchgrass	1%	2 water runons were performed 2 and 4 weeks following herbicide application Switchgrass removed dissolved atrizine and metalochlor by 52 and 59% of the runon, respectively Bare slope removed 41% of atrizine and 44% of metalochlor Grass plots retained most of the herbicide in the top 67 cm
Patty et al.	1997	France	no buffer 6m grass 12m grass 18m grass	7, 10, 15%	3 sites with **silt loam soils** ranging from 2 to 7% organic matter. Plots planted with ryegrass next to field cultivated to winter wheat Reduction of herbicides with increasing buffer width independent of runoff intensity Lindane - 72 to 100% Atrazine - 44 to 100% Isoproturon >99% Diflufenican >97%
Schmitt et al.	1999	NE	7.5 and 15m for all treatments 25 year grass plots mixed grass (2 yr) 50% grass 50% trees + shrubs (2 yr) grain sorghum (2 yr)	6 to 7%	**Silty clay loam** soils Permethrin concentrations reduced by 27-83%; atrazine by 5-43%; alachlor by 10-61%. (buffers not as effective for dissolved contaminants)
Seybold et al.	2001	OR	3m bare 3m switchgrass	1%	**Clay loam soil** There was no significant difference between bare and grass plots in amount of herbicide filtered. 72-88% of the leachate was filtered or adsorbed to the soil Switchgrass increased degradation rate of metalachlor but not atrizine. Overall, 56-73% of the amount of herbicide applied was removed

Vellidis et al.	2002	GA	8m grass 20m slash pine 10m hardwoods		**Loamy sand soil**; atrazine and alachlor were applied Restored forest riparian buffer Most of the surface transport of the herbicide occurred by June 30 Concentration reduction was greatest per meter flow within the grass buffer strip. Concentrations were or below detection limits near the stream

AUTHORS	DATE	STATE	BUFFER WIDTH AND TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
REVIEWS *in* Fischer and Fischenich (White Paper)	2004				
Mickelson et al.	1998	IA	4.6m grass filter strip 9.1m grass filter strip		Atrazine reduced by 31% and 80% in 4.6m and 9.1 m buffers, respectively
Rhodes et al.	1980		ns*		Trifluralin reduced by 96% and 86% for dry and moist filter strips, respectively
Asmussen et al.	1977		24.4m grassed waterway		2,4-D reduced in runoff by 98% and 94% for dry and wet antecedent conditions

*ns=not stated

MATRIX C - PHOSPHORUS

AUTHORS	YEAR	STATE	BUFFER WIDTH AND TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
PHOSPHORUS Barden et al	2003	KS	12.2m small trees+ native grass 12.2m small trees+fallow 12.2m fallow (7yrs) to allow for succession	*ns	**Silty clay loam**/natural rainfall+simulation Total P >50% reduction for all buffer types
Chaubey et al.	1994	AR	no buffer 3m grass 6m 9m 15m 21m	3%	**Silt loam soils** - swine manure applied at 200 N kg per ha 3.1m buffer reduced incoming PO_4 by 65% and the 21m buffer removed 94% 3.1m buffer reduced total P by 67% and the 21m buffer removed 92% Mass transport of these substances was reduced at 9m
Chaubey et al.	1995	AR	no buffer 3.1m uncultivated 6.1m 9.2m 15.2m 21.4m	3%	Uncultivated areas ammended with poultry litter 3.1m buffers reduced mass transport of PO_4 and total P by 40 % and 39%, respectively and by 91% and 90% respectively, in the 21.4m buffer
Daniels and Gilliam	1996	NC	1. fescue strip across lane into groundcover or mixed hardwoods and pines 2. narrow fescue to grass waterway through mixed weeds and small shrubs to larger trees	4-15%	Two locations #1 **Sandy loam to clay loam surface** horizons #2. **Silt loam / silty clay** 1 and 2 ephemeral and intermittent streams Vegetation structure; cultivated fields; natural rainfall Runoff total P was reduced by 50% but 80% of the soluble PO_4 passed through filters. Hi flows overwhelmed filters

Lee et al	2000	IA	no buffer 7.1m swithgrass 16.3 switchgrass-woody	5% (crop) 8% (buffer)	Switchgrass removed 72 % of total P and 44% PO_4-P Switchgrass-woody removed 81 and 35% total P and PO_4-P, respectively
Lim et al	1998	KY	0m tall fescue pasture 6.1m tall fesecue pasture 12.2m tall fescue pasture 18.3m tall fescue pasture	3%	**Silt loam soils** / simulated rainfall Almost all P in runoff was PO_4 not associated with sediment ~75% of total P and PO_4 was removed in first 6.1m of buffer strip
Lowrance et al.	2000	GA	8m grass Zone 1 40m thinned, clear cut, control Zone 2 15m undisturbed forest Zone 3	2.5%	Used USDA three zone system Movement of PO_4 was minimal and showed no spatial patterns
Majed et al.	2003	Canada	5m perennial ryegrass 2,5,10,15m legume + grass 5m bare 5m existing native grasses	2.3, 5%	**Silt loam soil** - 4% organic matter P trapping efficiencies ranged from 32 to 79% with increasing buffer width Authors did not compare all widths and vegetation types
Osbourne and Kovacic	1993	IL	no buffer-rowcrops to streambank 39m grass 16m mature forest	low relief	Dense basal till - silty clay loam Grass more efficient in reducing total and dissolved P During the dormant season both grass and forest acted as as a total P source
Osbourne and Kovacic (same article)		IL	10m ryegrass 20m ryegrass 30m ryegrass 20m oats		Oats had no significant effect on reducing total P removed in runoff 10m buffer had greater total P concentration than 30m buffer probably due to inundation resulting in P bound sediment deposited

Patty et al.	1997	France	no buffer 6m grass 12m grass 18m grass	7, 10, 15%	3 sites with **silt loam soils** ranging from 2 to 7% organic matter Plots planted with ryegrass next to field cultivated to winter wheat Soluble P in runoff was reduced from 22 to 90% with increasing buffer width
Schmitt et al	1999	NE	7.5 and15m 25 yr. grasss plots 7.5 and 15m 2 yr. mixed grass 7.5 and 15m 2 yr. 50% grass+ 50% trees / shrubs 7.5 and 15m 2 yr. grain sorghum	6 to7%	**Silty clay loam to sandy loam**; simulated rainfall Total P reduced by 55-79% 19-43% reduction of dissolved P simulated field runoff Most reduction was within first 7.5m Grass did not reduce concentrations of dissolved P compared with sorghum Significant width effect on volume and concentration of all contaminants
Snyder et al. 1998	1998	VA	10-40m wetlands 120m forest buffer	0-6% ag + upper woods 10-20% woods. 20%+ small wooded areas. 1-2% streams draining wetlands.	Soils vary with topography; acidic with high organic matter Corn-soybean rotation w. cover crop Water table ranged from 10m in ag field No spatial trend; concentrations generally higher in summer for most sampling locations (9m upper woodland, 2 to 9m on hillslope, 0 to 2m wetland)

Tate et al.	2000	CA	no buffer 10m pasture buffer	rolling foothills	Sprinkler and flood irrigated pasture composed of 40% clovers and 60% grass Pastures grazed from June to October Water use efficiency was low and distinct patterns were observed 15% to 69% of the irrigation water became runoff The authors found that more runoff per unit area was produced from pastures with buffers Buffer did not reduce total P concentration or load under sprinkler or flood irrigation but did reduce load of total P under flood irrigation

AUTHORS	YEAR	STATE	BUFFER WIDTH AND TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
REVIEWS					
in Osbourne and Kovacic	1993				Efficiency of removal of P - decease in concentration
					PERCENT REDUCTION
SUBSURFACE FLOW					
Peterjohn and Correll	1984		19 m forest		33%
Peterjohn and Correll	1984		50 m forest		114% (concentration increased)
SURFACE FLOW					
Cooper and Gilliam			16 m forest		50%
Peterjohn and Correll	1984		19 m forest		74%
Peterjohn and Correll	1984		50 m forest		85%
Dillaha et al.	1989		9 m grass		79%
Dillaha et al.	1989		5 m grass		61%
in Wenger, Seth	1999				
Vought et al .	1994	Sweden	8m grass		Grassed buffer retained 66% of PO_4-P in surface runoff ; after 16m, 95% retained
Mander et al.	1997	Estonia	20m and 28m		67 and 81% trapping efficiencies for 20 and 28m buffers, respectively
Dillaha et al.	1988		4.6m and 9.1m grass		71.5 and 57.5 respectively total P removal (exception, removed less in longer buffer)

Dillaha et al.	1989		4.6m and 9.1m grass		61% and 79% total P removed
Maguette et al.	1987		4.6m and 9.1m		41 and 53% respectively total P removal
Maguette et al.	1989		4.6m and 9.1m grass, grass/legume/bare/ native grass		18 and 46% respectively total P removal
Hubbard 1997	1997	GA	30m		No reduction of P in shallow groundwater. PO_4-P increased over the duration of the study
Peterjohn and Corell	1984	MD	50m		84% of total P and 73% of soluble PO_4-P were removed from surface runoff however, PO_4-P concentrations increased in shallow groundwater
Young et al.	1980		21m corn		Total P reduce by 67% and soluble PO_4-P reduced by 96%
Osbourne and Kovacic	1993		16m forest 39m grass		No reduction in phosphate from subsurface flow (from cropland)
in Fischer and Fischenich (White Paper)	2004				
Madison et al.	1989	ME	≥5m grass filter strip		Trapped ~90% of PO_4
Shisler et al.	1987	MD	≥19m forest		Removed 80% of excess PO_4
Lee et al.	2000	IA	no buffer		Grass removed 64% total P, 44% of PO_4
			7.1m switchgrass 16.3m switchgrass-woody		Grass/woody buffer removed 93% total P and 85% PO_4
in Uusi-Kamppa et al.	1997				
Syversen	1995	Norway	5,10,15m native grass	12-17%	Natural rainfall
					5m buffer trapped 45-65% of Total P and 2-77% of PO_4
					10m buffer trapped 56-85%% Total P and 0-88% of PO_4
					15m buffer trapped 73% of Total P and 10% of PO_4

Uusi-Kamppa and Ylaranta	1996	Finland	10m		Natural rainfall Buffer trapped 20-36% particle bound P and 0-62% PO_4
Uusi-Kamppa (unpublished)	1995	Finland	10m		Buffer trapped 53-78% particle bound P and 33% PO_4
Schwer and Clausen	1989	VT	26m		Dairy waste: 89% retention of Total P and 92% retention of PO_4. Greatest removal was during the growing season
Vought	1994	Sweden	8m 16m		8m buffer removed 66% of PO_4 16m buffer removed 95% of PO_4

*ns - not specified

MATRIX D - PATHOGENS

AUTHORS	DATE	STATE	BUFFER WIDTH AND TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
Atwill et al.	2002	CA	1m grass (simulation)	5, 10, 20%	Looked at three soil textures; **silty clay, loam;** sandy loam Surface and subsurface measurements Clay soils with lower infiltration were less effective in removing oocysts from buffer Postulated that buffers with higher infiltration rates and ≤20% slope and ≥3m wide should reduce concentrations of *Cryptosporidium parvum* by ≥99% although greater amounts of oocysts were found in subsurface flow of loam and sandy loam soils
Chaubey et al.	1994	AR	no buffer, 3m grass, 6m grass 9m grass, 15m grass, 21m grass	3%	**Silt loam soils** - swine manure applied at 200 N kg / ha There was a sigificant reduction in fecal coliform up to 3m but no significant reduction beyond 3m
Coyne et al.	1998	KY	4.5m grass sod 8m grass sod	9% (mean)	**Silt loam soils** Poultry waste/fecal coliform bacteria Mean fecal coli. trapping efficiency was 75% in 4.5m strip; most bacteria trapped in first 4.5m 91% in 9m strip Fecal streptococci trapping efficiency was 68% in 4.5m and 74% in 9m strip but coliforms were still 1000x higher than standard
Entry et al.	2000	GA	20m grass / 10m forest 10m grass / 20m forest 10m grass / 20m maidencane	1.5 - 2%	**Loamy sand (grass); loamy sand (riparian)** Swine wastewater fecal coliform Wastewater pulse moved farthest (30m) during wet seasons No differences to 2m in wells regardless of vegetative treatment

Entry et al. II.	2000	GA	20m grass / 10m forest 10m grass / 20m forest 10m grass / 20m maidencane	1.5 - 2%	**Loamy sand (grass); loamy sand (riparian)** Swine wastewater fecal coliform Total and fecal coliforms decreased with depth to 30cm 90 to 120 days amounts similar to non treated riparian filter strips
Lim et al.	1998	KY	no buffer 6.1m tall fescue pasture 12.2m tall fescue pasture 18.3m tall fescue pasture	3%	**Silt loam soils** / simulated rainfall No measurable concentrations of fecal coliforms after 6.1m
Tate et al.	2004	CA	1.1m grass (simulation)	5, 12, 20%	**Sandy loam soil** - 2 hour precipitation at 30 to 47.5 mm per hour. 5% slope had the greatest reduction Most of *Cryptosporidium parvum* oocysts were found in subsurface transport Most of *C. parvum* oocysts on 12 and 20% slopes were found in surface transport
Trask et al.	2004	IL	bare ground (simulation) bromegrass	1.5, 3, 4.5%	Used two rainfall intensities Higher intensity rainfall resulted in detection of *C. parvum* oocysts in surface flow Oocysts were found in surface and subsurface flow under lower rainfall intensity for both treatments. Vegetated treatment contained fewer oocysts than bare ground
Young et al.	1980	MN	Year 1- corn / orchardgrass / sorghum x sudangrass buffer 27.43m Year 2 buffer reduced to 21.34m (corn and oats)	4%	Fecal bacteria - feedlot Total coliform and fecal coliform reduced by 69% Fecal streptoccoci reduced by 70%

MATRIX E - NITROGEN

AUTHORS	YEAR	STATE	BUFFER WIDTH and TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
Barden et al	2003	KS	12.2m small trees+native grass 12.2m small trees+fallow 12.2m fallow (7yrs) to allow for succession	ns*	**Silty clay loam**/natural rainfall+simulation Total N reductions were between 45 and 55% depending on buffer type
Barfield et al.	1998	KY	4.6m bluegrass/fescue 9.1m 13.7m	9%	Conventional and no-till plots in a **karst** watershed (well structured soils with high infiltration rates) >90% nutrient trapping, 2001increasing with increasing buffer width
Bedard-Haughn et al	2004	CA	no buffer (irrigated pasture) 8m mixed grass 16m mixed grass	9.5 to 11.9%	**Rocky loam soils** / irrigated pasture Buffers decreased amount of ^{15}N tracer in runoff Majority of N attenuation was from vegetative uptake 8m buffer decreased NO_3 load by 28% 16m buffer decreased NO_3 load by 42% After 4 weeks there was a steady release of N in the runoff
Chaubey et al.	1994	AR	no buffer 3m grass 6m grass 9m grass 15m grass 21m grass	3%	**Silt loam soils** - swine manure applied at 200 N kg per ha Total Kjeldahl N reduced by 65% in the 3m and 92% in the 21m buffer Ammonia reduced by 71% in the 3m and 99% in the 21m buffer
Chaubey et al.	1995	AR	no buffer 3.1m uncultivated 6.1m grass 9.2m grass 15.2m grass 21.4m grass	3%	Uncultivated areas ammended with poultry litter Mass transport of total Kjeldahl N was reduced by 39% (3.1m buffer) and 81% (21.4m buffer) Ammonia was reduced by 47% (3.1m buffer) and 98% (21.4m buffer) Nitrate from incoming runoff was not reduced

Daniels and Gilliam	1996	NC	1. fescue strip across lane into groundcover or mixed hardwoods and pines 2. narrow fescue to grass waterway through mixed weeds and small shrubs to larger trees	4-15%	Two locations #1. **Sandy loam to clay loam surface** horizons #2. **Silt loam / silty cla**y 1 and 2 ephemeral and intermittent streams Vegetation structure; cultivated fields; natural rainfall Filters retained 20-80% of the NH_4 and 50% of the total Kjeldahl N and NO3 High flows overwhelmed filters
Dukes et al.	2002	NC	8 and 15m cool season grass 8 and 15m deep rooted grass 8 and 15m pine/mixed hardwood 8 and 15m native vegetation 0m (crops/pasture)		Wells at three depths Effect of vegetation not significant (however, there were confounding effects) results Deep wells, reduction of NO_3 was 69% (8m buffer) and 84% (15m buffer) At mid depth wells, reduction of NO_3 was 28% (8m buffer) and 43% (15m buffer)
Haycock and Pinay	1993	GB	16m ryegrass 16m Lombardy poplar	<1%	Floodplain with **impermeable clay** layer / arable land With increasing NO_3 load, NO_3 migrated upslope Poplar retained 99% of NO_3 Grass retained 84% of NO_3 in winter Vegetative biomass may contribute carbon to microbial pool even in winter
Hubbard et al.	1998	GA	10m + 20m coastal bermudagrass draining into forest 20m + 10m b.grass into forest 10m + 20m b.grass into maidencane	1.5-2%	NO_3 concentrations in runoff were greater with higher application rate and generally decreased with increasing buffer width Plots with maidencane had the highest concentration
Jacobs and Gilliam	1985	NC	<16m forest with and withought natural drainage	0-6%	Poorly drained to well drained soils / vegetable and grain crops with and without winter cover

Jones, Dryw	2001	CA	5m native forest 3% plant cover		5m buffers zones removed 45% of N No significant difference in slope and percent plant cover Measured surface flow
Jordan et al.	1993	MD	~60m forest	hillslope / floodplain	Reduced subsurface flow by 9% (initial amount less than drinking water standard) Most of NO$_3$ change occurred 25 to 35m from field at the edge of the floodplain in subsurface flow
Karr et al.	2001	NC	10 to>100m forest	ns	Pasture **sandy loams** / **riparian soils** are fine and loose sandy Swine waste application to fields NO$_3$ bypassed denitrification sites
Lee et al.	2000	IA	no buffer 7.1m switchgrass 16.3m switchgrass-woody	5% (crop) 8% (buffer)	Simulated rainfall - high infiltration rate Switchgrass removed 64% total N and 61% of NO$_3$ Switchgrass - woody buffer removed 89% total N and 92% of NO$_3$ Wider buffer trapped clay and soluble nutrients
Lim et al.	1998	KY	no buffer pasture (tall fescue) 6.1m pasture 12.2m pasture 18.3m pasture	3%	**Silt loam soils** / simulated rainfall ~75% of total N removed in first 6.1m. No significant reductions beyond 6.1m
Lowrance, Richard	1992	GA	50-60ft pine forest	2%	**Poorly drained loamy sand**/cropland NO$_3$ reduced by a factor or 7 to 9 in the first 10m In the next 40m, N reduced from 1.80 to .81mg NO$_3$-N per liter. Denitrification potential highest in August and October

Lowrance et al.	2000	GA	8m grass Zone1 40m thinned, clear cut, control Zone 2 15m undisturbed forest Zone 3	2.5%	Used USDA three zone system Groundwater NO$_3$ reduced from 11-22mg per L to less than 2mg per L within 5m into the forest No Zone 2 forest management effects on NO$_3$ concentrations
Mendez et al.	1999	VA	no buffer 4.3m grass 8.5m grass	ns	NO$_3$ concentrations reduced by 51% (4.3m) and 52% (8.5m) NH4 concentrations reduced by 58% (4.3m) and 65% (8.5m)
Osbourne and Kovacic	1993	IL	no buffer (row crops) 39m grass 16m mature forest	low relief	Dense basal till - **silty clay loam** ≥90% reduction in NO$_3$ in both grass and forest buffers No seasonal variation seen for NO$_3$ concentrations
Patty et al.	1997	France	no buffer 6m grass 12m grass 18m grass	7, 10, 15%	3 sites with **silt loam** soils ranging from 2 to 7% organic matter - Natural runoff events Plots planted with ryegrass next to field cultivated to winter wheat NO$_3$ was reduced from 44 to 100% with increasing buffer width Perpendicular planting improved water quality
Peterjohn and Correll	1984	MD	50m riparian forest	ns	**Deep fine sandy loam with clay sublayer** Total reductions were 79% for NO$_3$, 62% for NH$_4$ and 62% for organic N Mean annual concentrations decreased between 90 and 98% Most of the reduction occurred in the first 19m of forest
Pinay et al.	1994	France	50m riparian forest transect	3%	**Clay and fine silt soils** All NO$_3$ removed from first 30m of buffer

Schmitt et al.	1999	NE	7.5 and15m 25 yr. grasss plots 7.5 and 15m 2 yr. mixed grass 7.5 and 15m 2 yr. 50% grass+ 50% trees / shrubs 7.5 and 15m 2 yr. grain sorghum	6 to7%	**Silty clay loam to sandy loam**; simulated rainfall Buffers had greater effect on sediment bound than dissolved nutrients NO_3 reduced by 24-48% all contaminants
Schnabel et al.	1996	PA	40m woody 18m grass	gently rolling alluvial floodplain	buffer NO_3 levels lowest near stream in both buffers Carbon was limiting in the woody buffer
Snyder et al.	1998	VA	10-40m wetlands 120m forest buffer	0-6% ag + upper woods 10-20% woods 20%+ small wooded areas 1-2% streams draining wetlands	Instream NO_3 concentrations 48% less than in field; NH4 no spatial trend was seen. Concentrations were higher in summer
Spruill, Timothy	2000	NC	30m lowland forest 0m		**Poorly drained soils** in stream valleys NO_3 was 95% less in buffered vs non buffered sites 65 to 70% was due to reduction and denitrification (remaining due to dilution)
Tate et al.	2000	CA	no buffer 10m pasture buffer	rolling foothills	Sprinkler and flood irrigated pasture composed of 40% clovers and 60% grass Pastures grazed from June to October Water use efficiency was low and distinct temporal runoff patterns were observed 15% to 69% of the irrigation water became runoff No significant reduction in NO_3 concentrations and loads

Verchot et al.	1997a	NC	54.9m pine/hardwood 67m pine/hardwood	1 - 4% 2 - 9%	Surface flow / natural runoff events Watershed 1 - fields were sandy loam (clayey) and loamy sand in forest Watershed 2 - fields were loamy sand / sandy loam and sandy loam forest Annual rotation of winter wheat and soybean with tobacco every 3 years Buffer zones ineffective in winter and spring. NO_3, NH_4 and organic N loading increased in W1- retention effective in W2. Clay soils implicated
Verchot et al.	1997b	NC	54.9m pine/hardwood 67m pine/hardwood	WS 1 - 4% WS 2 - 9%	Subsurface flow / natural runoff events Watershed 1 - fields were **sandy loam (clayey) loamy sand** in forest Watershed 2 - fields were loamy sand / sandy loam and **sandy loam** forest tobacco every 3 years NO_3 loss almost entirely from denitrification of N. NO_3 concentrations decreased to almost 0 from to forest edge at both sites
Wigington et al.	2003		no buffer (ryegrass seed crop) 30-48m noncultivated grass, forbs, sedges and rushes	<3%	**Poorly drained soils** Buffer significantly reduced NO_3 in shallow groundwater for all sampling dates however, in-field practices should be implemented first since most of flow comes from saturated swales in fields and generally bypasses the riparian zone

AUTHORS	YEAR	STATE	BUFFER WIDTH and TYPE	SLOPE	BENEFIT - TYPE AND % REDUCTION
REVIEWS					
in Osbourne and Kovacic	1993				
SUBSURFACE FLOW					TYPE and PERCENT REDUCTION
Bagley and Gallagher			10m forest		60-98% seasonal variation
Dillaha et al.	1989		9 m grass		73%
Dillaha et al.	1989		5 m grass		54%
Doyle et al.	1977		30 m forest		98%
Lowrance et al.	1984		25m forest		68%
Pinay and Decamps	1988		30m forest		100%
Schnabel	1986		19m forest		40-90m seasonal variation
Schnabel	1986		27m grass		10-60% seasonal variation
SURFACE FLOW					
Young et al.	1980		27 m grass	4%	grass 84%
in Castelle et al.	1994				
Bingham	1980		1:1 ratio of buffer area to waste area (cumulative surface area of poultry cages)		Sufficient to reduce nutrient runoff to background levels
Doyle et al.	1977		3.8m forest 4m grass		Reduced N, P, K and fecal bacteria levels
Lynch	1985		30m		water standard"10mg/L
Madison et al.	1992		4.6 vegetated filter strip		Filter strip trapped 90% of N from 2 simul. storm events. 9.1m buffers had 96-99.9% trapping efficiencies with no improvement beyond 9.1%
Overcash et al.	1981		grass		1:1 ratio of buffer area to waste area needed to reduce concentrations of animal waste by 90-100%
Vanderholm and Dickey	1978		91.5m, 262m	0.5, 4%	Removed 80% of the nutrients from overland flow
Xu et al.	1992	NC			NO$_3$ concentrations reduced from 764mg NO$_3$/kg soil to 0.5mg/kg soil

in Wenger, Seth	1999				
Fennesey and Cronk	1997		20-30m		Can remove 100% of NO_3
SURFACE RUNOFF					
Daniels and Gilliam	1996	NC	6m grass 13m grass/forest 18m grass/forest		Retained 20-80% of NH_4 and 50% of both total and NO_3 (sites had different characteristics)
Dillaha et al.	1988		4.6m, 9.1m		Effective for removing total N but not NO_3 67% reduction (4.6m buffer) and 74% (9.1m buffer)
Dillaha et al.	1989		4.6m, 9.1m 9.1m		NO_3 reduced by 73%
Hanson et al.	1994		31m		Reduced shallow groundwater NO_3 concentrations by 94% to less than drinking water standard (downslope from septic)
Lowrance	1992		50-60m		reduction in first 10m reduction in first 10m
Maguette et al.	1987		4.6m, 9.1m		17% and 51%, respectively
Maguette et al.	1989		4.6m, 9.1m		0% (for both buffer widths)
Mander et al.	1997		20m, 28m		81 and 80% total groundwater N removal efficiencies, respectively
Osborne and Kovacic	1993	IL	16m forest		Reduction of shallow groundwater NO_3 levels of 96%
Peterjohn and Correll			50m		Reduced all N in surface runoff + NO_3 in shallow groundwater; other forms increased
Pinay and Descamps	1993		30m		Sufficient for N removal
SHALLOW SUBSURFACE FLOW					
Vought	1994		8m 16m		Surface reductions of NO_3 were 20% and 50% for grass buffers. Subsurface flow approached 100%, 10 to 20m into the buffer

in Allan R. Hill	**1996**				
Lowrance et al.	1984	GA	forest		Shallow lateral flow in a shallow aquifer in a deciduous forest retained 90% of the NO_3
Schnabel	1986	PA	18m grass		Shallow lateral flow with bedrock at 1m - NO_3 retention was >90%
Pinay and Decamps	1988	France	130m forest		Shallow lateral flow with clay at 4m depth - NO_3 reduced 100%
Cooper	1990	NZ	9m grass		to 1m - 1m. Reduced NO_3 by >90%
Robertson et al.	1991	Canada	20m grass		Groundwater flowing up with a sand aquifer >10m below the surface - NO3 reduced by 66-98%
Simmons et al.	1992	RI	31m forest		outwash outwash. NO_3 reduced by >80%
Brusch and Nilsson	1993	Denmark	15-25m fen		Overland flow at depth with 2-3m peat over deep sand
Phillips et al.	1993	MD	forest		Upward flow in 7 to 20m sand aquifer - Low retention of NO_3
Schipper et al.	1993	NZ	pine forest		Upward shallow lateral flow in shallow organic soil over clay removed 98% of NO_3

(NO_3 inputs ranged from 0.6 to 44 mg NO_3^-/L)

*ns=not specified

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