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RIPARIAN VEGETATION EFFECTIVENESS

TECHNICAL BULLETIN NO. 799

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by

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PRESIDENT'S NOTE

Vegetated buffers along streams are effective in controlling impacts of forest management activities on water quality and aquatic habitat. Extensive research by NCASI and others has shown that vegetative buffers used in combination with other control measures provide high levels of stream protection in most forestry settings.

The width of vegetated buffers needed to protect streams has become a controversial topic. Very wide buffers are being advocated by some ecologists and are being incorporated in various government regulations and guidelines. The economic costs of very wide buffers are significant and quantifiable, but the ecological benefits are not well defined.

This technical bulletin reviews the scientific literature on ecological functions of riparian vegetation and uses published data to describe functional relationships between buffer width and ecological benefits. In general, these relationships are non-linear such that the marginal benefit of increasing buffer width is greatest at low width values and becomes progressively smaller at higher width values.

The analytical framework described in this bulletin does not consider site-specific factors that can alter general relationships between buffer width and ecological benefits. NCASI recognizes, for example, that the effectiveness of stream buffers can be compromised by failure to implement best management practices outside the riparian zone. The general relationships described herein should not be viewed as definitive but rather as general technical input to forest policy analysis and land management planning. We hope this bulletin and related NCASI projects will help move the debate on stream buffers beyond general expert opinions and redirect attention to a substantial body of relevant scientific data.

Ronald A. Yeske
February 2000

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ABSTRACT

Vegetated buffers are often used to reduce or eliminate impacts to streams from nearby land uses. This study examines the ecological functions of riparian vegetation and graphically summarizes relationships between buffer width and effectiveness. Ecological functions considered are streambank stabilization, sediment reduction, chemical removal, production of large organic debris, production of particulate organic matter, and shade production for stream temperature moderation.

For five of the six functions considered, the effectiveness of riparian buffers increases with buffer width. Most of the potential contributions of riparian vegetation to these functions are realized within the first 5 to 25 m from the stream bank. Buffer widths in this range typically provide at least 50 percent of potential effectiveness, and often 75% effectiveness or greater. Disproportionately wider buffers are needed to achieve greater effectiveness (i.e., the marginal benefit of making buffers wider usually declines rapidly as buffer widths increase beyond 5 to 25 m).

Contributions of vegetated buffers to streambank stability do not seem to be greatly affected by buffer width in most circumstances. Instead, streambank stability was found to depend mainly on fine root density within the bank itself, and on several intrinsic soil parameters.

Buffer width is only one of several factors affecting riparian functions and stream protection. The number, size, and vigor of living trees in the buffer can affect infiltration and evapotranspiration, and thus affect transport of sediment and chemicals. Dead trees lying on the ground and dense understory vegetation in the buffer can provide significant barriers to sediment movement. Additional factors affecting riparian function and stream protection include width of flood-prone area, soil physical properties, and sideslope gradient above the stream. In some instances, these physical characteristics (and their interactions with management practices and natural processes) may be larger determinants of stream protection than vegetative metrics.

KEYWORDS

riparian management, best management practices, stream buffer, filter strips, bank stability, large woody debris, particulate organic matter, sediment control, chemical control, stream shade

RELATED NCASI PUBLICATIONS

Technical Bulletin No. 672 (July 1994). *Forests as nonpoint sources of pollution, and effectiveness of Best Management Practices*.

Technical Bulletin No. 631 (June 1992). *The effectiveness of buffer strips for ameliorating offsite transport of sediment, nutrients, and pesticides from silvicultural operations*.

Technical Bulletin No. 775 (January 1999). *Assessing Effects of Timber Harvest on Riparian Zone Features and Functions for Aquatic and Wildlife Habitat*.

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RIPARIAN VEGETATION EFFECTIVENESS

1.0 INTRODUCTION

1.1 Background

Streams may be subjected to disturbances that originate outside of riparian zones. These disturbances can result in changes in the biological, chemical, and physical properties of streams. As a result of external influences, streams and their biota may be exposed to higher temperatures, sediment and chemical loading, and streambank erosion. Further, adjacent land uses may reduce the availability of many essential components of productive streams.

The potential for intensive management to adversely impact streams is of concern for many land uses, including silviculture. Stand management and timber harvest activities may include unpaved road construction and maintenance, truck travel, drainage alteration, timber harvesting and skidding, clearing and grading, fertilizer and pesticide application, and slash burns. As a result, erosion rates, chemical loading in both surface and ground waters, and surface water temperatures may increase for at least short periods following these activities. Additionally, the potential for producing large organic debris (LOD), particulate organic matter (POM), and roots for soil stabilization may decrease. Any or all of these potential impacts may adversely affect stream water quality and aquatic habitat.

Several means exist for reducing environmental impacts from silvicultural practices. One, for example, is to alter stand management and timber harvest practices through the use of Best Management Practices (BMPs) to reduce on-site generation of sediments or chemicals. Another BMP developed for maintaining stream function is the use of buffers. “Buffers” are vegetated zones located between natural resources (such as streams, wetlands, or critical wildlife habitat) and nearby areas subject to human alteration.

In some locations, buffers are known as “vegetated filter strips,” or VFSs. The emphasis on the filtering functions of vegetation is derived from its widespread use to remove sediments and other waterborne pollutants from surface runoff. In this capacity, vegetated buffers or the plants themselves may be thought of as “sinks,” in that their presence results in a net reduction of pollutants entering streams. However, plants may play a role in maintaining riparian functions beyond sediment and chemical removal. For example, plants are the primary source of essential stream components such as LOD, POM, and shade for water temperature moderation.

The focus on the vegetative component of buffers–instead of on other buffer elements such as slope or soil type–results because vegetation is the one variable over which land managers may exert the most control. For example, specific plant species may be planted in or removed from buffer areas to optimize buffer effectiveness.

1.2 Objective

Given that the vegetative component of buffers can be controlled, one of the challenges that managers of silvicultural lands face is determining how large a riparian buffer needs to be to protect streams while not “over sizing” the buffer; buffers that are too narrow will not adequately protect streams, but buffers that are wider than necessary result in the economic loss of uncut trees. Properly sizing buffers requires an understanding of the roles that vegetation plays in maintaining riparian function, and an understanding of the incremental increases or decreases in riparian functional effectiveness that result from increasing or decreasing buffer widths. Therefore, the objective of this bulletin was to evaluate and, to the extent possible, quantify the effect of riparian vegetation on riparian maintenance, as a function of distance (width) measured from stream channel banks. Moreover, this report focuses on silvicultural management in the Pacific Northwest, although the results of studies conducted elsewhere in the U.S. and abroad were used where applicable.

This bulletin consists of an extensive literature review and specifically examines the effectiveness of vegetated riparian buffers in providing six essential riparian functions: three "sink" functions–streambank stabilization, sediment reduction, and chemical removal, followed by three "source" functions–LOD production, POM production, and shade production for stream water temperature maintenance. Vegetation effects on these functions are mostly described in terms of distance from a stream bank expressed in meters; where appropriate, other metrics are used (such as root density or tree height).

1.3 Effectiveness

This bulletin also includes "effectiveness" graphs for each function. These graphs, derived from published data, are intended to represent the relationship between buffer size and vegetation effectiveness. Developing effectiveness curves depends in part on establishing endpoints on the curves, that is, 0 and 100% effectiveness. For purposes of this report, 0% effectiveness means that there is no *vegetative* influence on a particular riparian function at all. For example, 0% vegetative effectiveness with respect to sediment trapping means that all sediment generated would move downslope unless impeded by an abiotic feature (such as a depression). Note that the influence of abiotic factors such as slope gradient or soil type were not considered in constructing the graphs.

One hundred percent effectiveness means that the riparian functions are at "background" levels, or those which would have occurred if there were no nearby anthropogenic land uses. In the sediment example above, 100% effectiveness means that the amount of sediment delivered to streams would be identical to that delivered under pristine conditions. Because in nearly all locations some sediment is delivered to streams even under pristine conditions, 100% effectiveness for sediment trapping may not mean that *no* sediment is deposited in streams, only that there would be no *increase* in the amount of sediment relative to the background, or reference, condition.

1.4 Limitations

Using this "effectiveness" approach has several limitations. First, in many instances background conditions are not known. This is because in many locations measurements of background conditions were never made before land management practices were implemented. Studies of reference conditions in other similar locations may be substituted, but because of the variability between even similar sites, comparing existing (managed) conditions from one location to reference (pristine) conditions from another necessarily introduces a degree of error. The effectiveness graphs, intended to show a single relationship between distance and effectiveness, are derived from a collection of data points from a variety of studies. These studies, while related in some ways, may not be directly comparable, but are useful for identifying general trends.

Second, many of the studies used to compile this report provide data for a single buffer size but did not investigate the effects of changing buffer sizes. This is because in many locations buffer sizes have long been established, therefore researchers have only the effectiveness of a single buffer width to examine. Some of the studies reviewed for this bulletin reported that a buffer of a single width was effective to some degree with respect to a given riparian function. In those studies, however, no data were provided demonstrating or even indicating what the relative effect of doubling or halving the buffer width, for example, would have been.

Further, many studies provided only qualitative results, stating only that a buffer of a certain width was or was not effective with respect to some riparian function, without quantifying the degree of effectiveness. Since "effective" was rarely, if ever, defined, these data were not used for preparing the effectiveness graphs.

Finally, while the intent of this report was to concentrate on studies conducted in the Pacific Northwest, the incorporation of other studies was necessary. Because of regional differences in climate, soils, management practices, and other factors, data from these studies may be useful for identifying general trends, but may not be directly applicable to Pacific Northwest sites.

1.5 Methods

The following recent literature reviews provided much of the initial information used in this report: Castelle, Johnson, and Conolly (1994); Belt, O'Laughlin, and Merrill (1992); Castelle et al. (1992a,b); and Johnson and Ryba (1992). Note that the three Castelle et al. publications focused on wetland buffers, but because riparian buffers and wetland buffers are often required to perform identical functions, much of the information in those reviews was pertinent.

Information summarized in each of these reviews was re-examined in light of the specific objectives of this bulletin. An additional literature search was conducted using a computer-based search system at the University of Washington. Several NCASI members also contributed data and reports which were not included in the university's database. Papers and other information (such as that obtained from phone conversations and during meetings) were prioritized in the following manner. First priority was given to studies conducted in silvicultural areas in the Pacific Northwest. Second priority was given to silvicultural studies conducted in other part of the U.S., and then to silvicultural studies conducted abroad. Third priority was given to non-silvicultural studies, such as those which examined buffer systems other than riparian forests. Lower priority was given to studies conducted in agricultural areas; some agricultural studies were not included in this report because of the differences between agricultural and silvicultural practices and resulting potential impacts (for example, nutrient loading from livestock pens is typically of a different order of magnitude than that from logging operations). Other agricultural studies were deemed applicable, particularly when forested buffers were used to protect riparian areas from agricultural impacts. Some generic studies that examined strictly physical parameters were also used; these studies are noted in the report. The resulting information was summarized and included in this report. Gaps in current information and research needs were identified, and are presented in the final section of this report.

2.0 STREAMBANK STABILIZATION

Streambank stability is determined by numerous factors. Kleinfelder et al. (1992) characterized streambank maintenance as a balance of forces and influences. These forces and influences include soil properties such as moisture content and texture, natural erosive forces such as overland flow, and external variables such as vehicular, wildlife, and livestock trampling, grazing, and upstream hydrologic modifications such as dams and channelization. High moisture content, coarse soil textures, high stormwater and meltwater runoff, surface compression, and upstream channelization tend to accelerate the rate at which soil particles become detached and therefore increase streambank destabilization (Henderson 1986).

Other factors have a stabilizing influence on streambanks. These include the cohesive, frictional, and interlocking properties of soil (Wray 1986), riparian vegetative characteristics, and the abundance or density of streambank roots (Thorne and Tovey 1981). Some soil properties are influenced in part by vegetation. However, a detailed discussion of intrinsic soil stabilizing properties is beyond the scope of this report; the stabilizing influence of vegetation is the primary focus of this section.

Vegetation may stabilize streambanks by reducing soil moisture content through uptake and subsequent transpiration. Low soil moisture content in turn may reduce soil pore water pressure (for example, when soils are saturated) that might otherwise lead to bank instability. Therefore, plant species with greater transpiration rates may provide greater streambank stability than those with lower rates. The environmental variables that most strongly influence transpiration are irradiance and atmospheric saturation deficit (Waring and Schlesinger 1985). Transpiration rates from forests may be similar for a wide range of species, and may not vary widely over a range of sizes and plant densities, particularly for species with a Leaf Area Index (LAI) of greater than 3.0 (Doley 1981; Jarvis 1981). However, transpiration rates may vary among other species, and may be dependent in part on tree spacing. In such cases, a small number of large, widely-spaced trees may transpire at greater rates than numerous small, densely-spaced trees (Waring and Schlesinger 1985). This is because exposed trees tend to maintain more open stomata and have higher air/leaf water vapor deficits than trees growing in closed stands (Whitehead and Jarvis 1981).

Perhaps one of the most important streambank stabilizing forces is the influence of roots. One early study in this area, Zimmerman, Goodlett, and Comer, (1967), suggested that herbaceous roots increased streambank cohesiveness and strength. This was supported by their observations that the width-to-depth ratio of a stream was three times greater in forested reaches (ratio equal to 6.1) than in meadow reaches (2.0). However, roots of woody plants may also play an important role in streambank stabilization, particularly deep-rooted trees and shrubs. Deep roots can penetrate the soil profile and become anchored in more stable strata such as weathered or fractured bedrock. The tensile strength of the roots can resist shear stresses of streambank soil (Waldron 1977; Schlosser and Long 1974). From a management perspective, it is interesting to note that the tensile strength of roots varies by region, species, and root diameter. For example, the average tensile strength of roots of Rocky Mountain Douglas fir was found to be less than half than that of Coastal Cascade Douglas fir (Burroughs and Thomas 1977). Spruce-hemlock roots are about one-third as strong as birch (Wu 1976; Turmanina 1965). Irrespective of tree species, root strength is inversely proportional to root diameter (Burroughs and Thomas 1977; Wu 1976; Turmanina 1965).

Further, the majority of tree roots extend radially from the trunk about as far as the crown does (to the “drip line”). Therefore, beyond this distance, which is a function of tree species and age, tree roots will have significantly diminished influence on streambank stability.

It has also been suggested that streambank undercutting is possible because streambank collapse is prevented or at least delayed by roots (Richards 1977). Note that other vegetative factors, such as the presence of large woody debris which may have the effect of armoring streambanks, may also influence streambank stability; a discussion of vegetative effects on LOD recruitment is presented in a later section.

Waldron and Dakessian’s (1982) examination of the influence of plant roots on soil stability included seven grass species, two legumes, and two trees. These investigators measured direct shear resistance in packed soil columns. Generally, their findings support the observations of Zimmerman, Goodlett, and Comer (1967) and others, in that herbaceous roots were found to provide significant soil stabilization. However, they noted that the roots of all species examined increased soil strength to varying degrees. Specifically, many of the grass species planted in early autumn produced nearly a three-fold increase in soil shear resistance by late spring (less than eight months after planting). Tree roots (*Pinus ponderosa* and *Quercus agrifolia*) were also found to provide soil shear resistance of this magnitude, but only after tree saplings were three to nearly five years old.

While early studies focused on the direct shear resistance of soils (Waldron and Dakessian 1982; Brenner and James 1977; Endo and Tsurata 1969), Kleinfelder et al. (1992) examined streambank collapse due to compressive forces such as those imparted by livestock trampling. These forces differ in that direct shear causes soil failure along horizontal planes, while compression causes shearing in inclined (diagonal) or vertical planes (Wray 1986). Because near-surface alluvial soils develop only small confining pressures (Wray 1986), streambank shearing is probably best simulated through unconfined compression tests (Kleinfelder et al. 1992). Kleinfelder et al. (1992) concluded that soil resistance to shearing increased with increased strain, indicating an elastic reinforcement condition of the roots. They also noted that the important relationship between root-length density and compressive strength of noncohesive soils was non-linear, with substantial increases in strength occurring from moderately dense root systems–about 2 mm/mm^3. Beyond that point, increased root-length density increased soil strength by progressively smaller amounts, reaching an apparent asymptote at approximately 50 kPa (Figure 1). They also found that the roots of different plants provided varying amounts of compressive soil strength; in their study, *Carex nebrascensis* imparted the greatest compressive soil strength. Figure 2 depicts an effectiveness graph of streambank stability versus root density. Because of the relationship between root density and unconfined compressive strength, the shape of Figure 2 is identical to that of 1, with the apparent 50 kPa limit of Figure 1 presented as 100% effectiveness on Figure 2. Lastly, however, Kleinfelder et al. (1992) noted that stream morphology characteristics had little correlation with compressive strength, root-length density, or other independent variables, suggesting other factors may have an equal or greater influence on stream morphology.

3.0 SEDIMENT REDUCTION

Plants have long been known to reduce soil erosion caused by direct rainfall and overland flow (Waldron and Dakessian 1982). The ability of trees to attenuate the direct impacts of raindrops is a direct function of areal cover. Rainfall that is intercepted prior to contact with the soil surface is also more likely to be infiltrated or evaporated, consequently reducing both the volume and peak rate of stormwater runoff. For example, Pitt, Gould, and LaSota (1986) suggested that forested areas may produce 30 to 50% less runoff than grassed areas. The ability of trees to reduce runoff is important because, particularly on slopes in silvicultural areas, overland flow has great potential for causing soil erosion and subsequent sedimentation of streams. Accordingly, the majority of the research in sediment control has focused on surface water movement.

Vegetation can attenuate erosion and sedimentation from overland flow in numerous ways. For example, exposed tree roots and downed trees may block flow by forming a physical barrier which slows surface flow rates and mechanically traps sediment and debris. Vegetation also stabilizes streambanks which could otherwise erode and deposit sediment directly in streams, and promotes infiltration (Shisler, Jordan, and Wargo 1987). Vegetation limits erosion and subsequent sedimentation by increasing soil strength. The ability of roots to maintain soil structure and increase soil strength is discussed above (see Streambank Stabilization section).

In addition to attenuating erosion, another advantage of the increased soil strength that roots impart is that surface soils become more resistant to channelization. As channelized flow is minimized, sheetflow generally increases. This is important because flow rates are generally lower for sheetflow than for channelized flow. Therefore, where vegetation helps resist the formation of channels, water will flow more slowly, allowing more time for settling of sediments and infiltration.

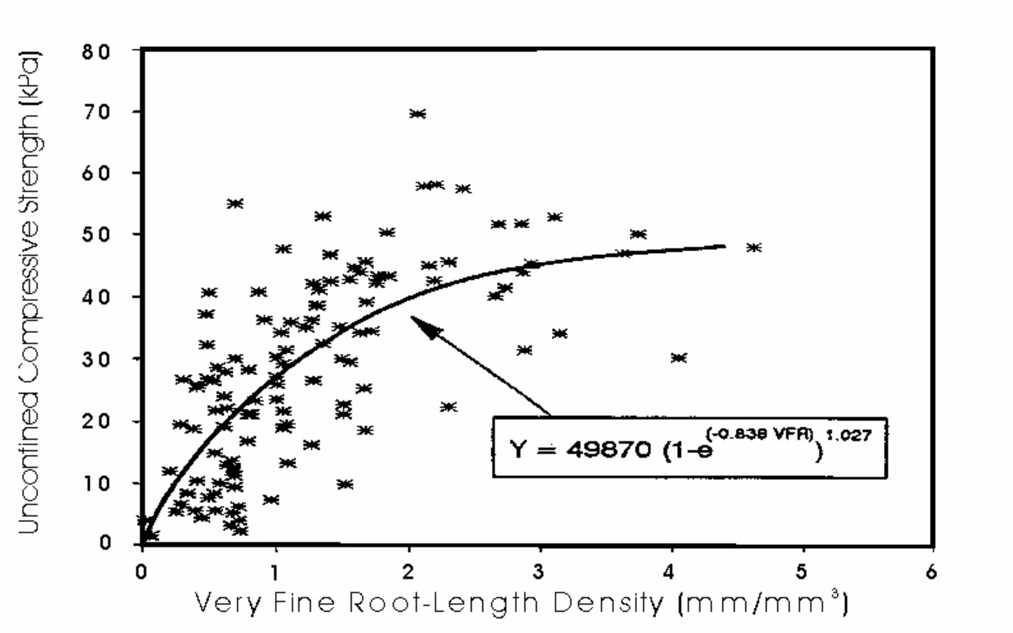


Figure 1. Very Fine Root-Length Density vs. Unconfined Compressive Strength at 40% Deformation (reprinted with permission from Kleinfelder et al. 1992)

Dunne and Leopold (1978) stated that on most forest lands, soil erosion rates are low. They provide "relative" soil erosion rates for numerous vegetative cover types in the Pacific Northwest. According to their summary, because of the presence of forest duff (Oi and Oe horizons), erosion of forest soils is comparable to that of permanent pasture, about 10 times less than that for wheat stubble, about 45 times less than that for orchards and vineyards, and approximately 50 times less than that for row crops (under conventional tillage). Note that the presence of a duff layer is not necessarily dependent on the continuous presence of standing trees, but the long-term absence of trees would be expected to result in a decrease in duff material.

In silvicultural areas, logging roads are often the primary source of sediments (Megahan et al. 1986; Dunne and Leopold 1978; Beschta 1978; Burns 1972; Packer 1967). In particular, logging road construction is often a source of eroded soils. Megahan, Day, and Bliss (1978) found that nearly two-thirds of road-related landslides occurred on road cuts. Brown (1985) noted that riparian buffers are "of little value in handling erosion from side slopes above the buffer in most of the mountainous West." This is because in many of the soils of this area, channelized flow is common. When runoff occurs as channelized flow, the physical trapping provided by living and downed vegetation may be by-passed by sediment-laden water.

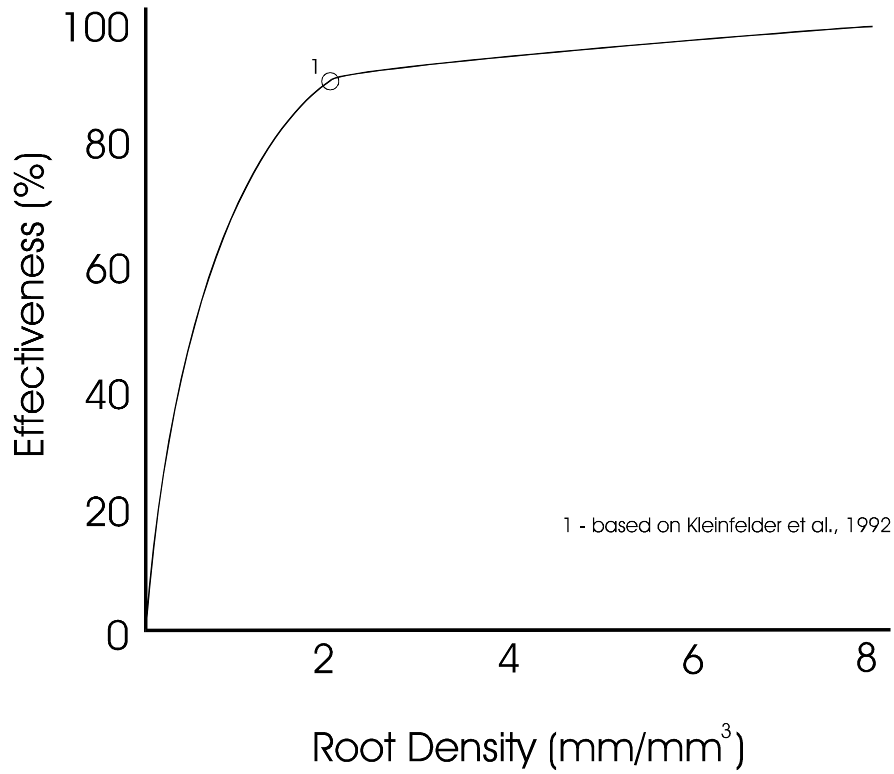


Figure 2. Effectiveness of Vegetation: Streambank Stabilization

Horner and Mar (1982) reported that a 61 m grassy swale removed 80% of suspended solids; Broderson (1973) also found that buffers which are 61 m wide control sedimentation effectively, even on steep slopes. According to Lynch, Corbett, and Mussallem (1985), a 30 m buffer between logging activity and wetlands and streams removed an average of approximately 75 to 80% of the suspended sediment in surface runoff. In that study, greater sedimentation yields resulted from forested areas which had been commercially clear-cut and then denuded with an herbicide because of channelization which developed following these activities. In an agricultural setting, Ghaffarzadeh, Robinson, and Cruse (1992) examined sediment removal by grass VFSs ranging from 0 to 18.3 m on 7 and 12% slopes. They found no difference in VFS performance on either slope beyond 9.1 m, where 85% of the sediment was removed. Further, there was no difference in sediment removal between the two slope angles beyond 3.1 m.

Wong and McCuen (1982) derived an equation to determine effective buffer widths based upon sediment particle size, slope, surface roughness, and runoff characteristics. While small buffers were found to remove small amounts of sediments, the relationship between buffer width and percent sediment removal was non-linear. Disproportionately large buffer widths were required for incrementally greater sediment removal. For example, if the sediment removal design criteria were increased from 90 to 95% on a 2% slope, then the buffer widths would have to be doubled from 30.5 m to 61 m.

Figure 3 presents an effectiveness graph of sediment trapping efficiencies. The shape of this graph indicates a non-linear relationship between buffer width and trapping effectiveness. A large part of the reason for this relationship is due to the distribution of soil particle sizes, and the differing rates at which particles of different sizes may drop out of runoff. For example, eroded materials originating from a logging road cut may include a range of particle sizes from clays to sands, as well as gravels and larger rocks. According to Stoke's Law, which states that particle settling velocity is proportional to the square of the particle's radius, the larger particles will settle out along the slope first.

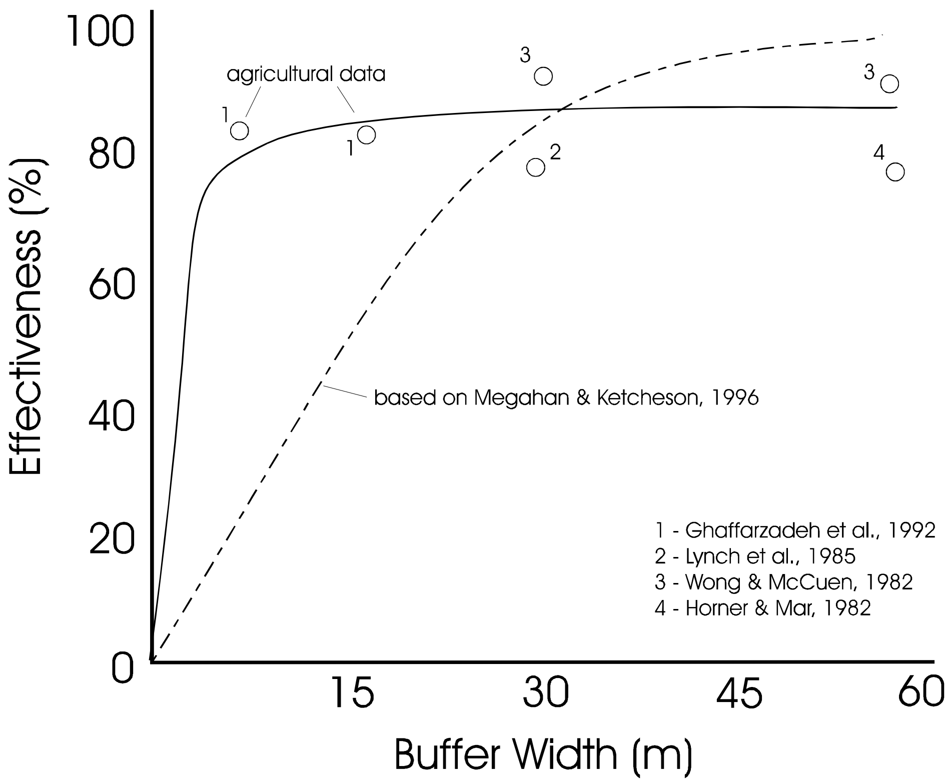


Figure 3. Effectiveness of Vegetation: Sediment Removal

This type of non-linear relationship was also reported by Megahan and Ketcheson (1996), who found that sediment travel distance was directly proportional to sediment transport energy and sediment volume, and inversely proportional to slope storage potential and the median particle size of eroded material. Of these factors, both standing (dead and live) and downed trees may add to the slope storage potential by providing obstructions to runoff or by creating slope surface irregularities. Thus, an increasing amount of vegetation would provide for greater sediment trapping. While the non-linear relationship presented in Figure 3 would remain due to particle size considerations, somewhat narrow but densely planted communities may provide equivalent trapping efficiencies to wider but more thinly planted areas.

4.0 CHEMICAL REMOVAL

Riparian vegetation can remove metals, nutrients, and other chemicals from runoff by filtering water, via plant uptake, and by facilitating bacterial transformations. Young, Huntrods, and Anderson (1980) reported that buffer strips on a 4% slope reduced total N and P by an average of 84 and 83%, respectively. Peterjohn and Correll (1984) found 89% N retention and 80% P retention in a riparian forest. Further, they suggested that the major pathway of N loss in riparian forests was in subsurface flows. Jordan, Correll, and Weller (1993) also noted the importance of shallow groundwater as the hydrologic component in which most N is removed from downslope flows. They suggested that both plant uptake and denitrification may be important processes determining N removal, but found that N was not being transformed into either NH_4 or dissolve organic N (DON). Similarly, Lowrance et al. (1984) attributed nutrient loss in riparian forests to plant uptake, and recommended periodic harvests of riparian vegetation to ensure net nutrient removal. However, while Jacobs and Gilliam (1985) also reported significant NO_3 loss in shallow groundwater passing through riparian forests, they found that assimilation by vegetation was insignificant; they attributed the majority of the NO_3 loss to denitrification. Xu, Gilliam, and Daniels, (1992) found that NO_3 concentrations were reduced from 764 mg NO_3-N kg^{-1} soil to approximately 0.5 mg NO_3-N kg^{-1} soil in a 10 m mixed herbaceous and forested buffer strip in the North Carolina Piedmont (see Figure 4).

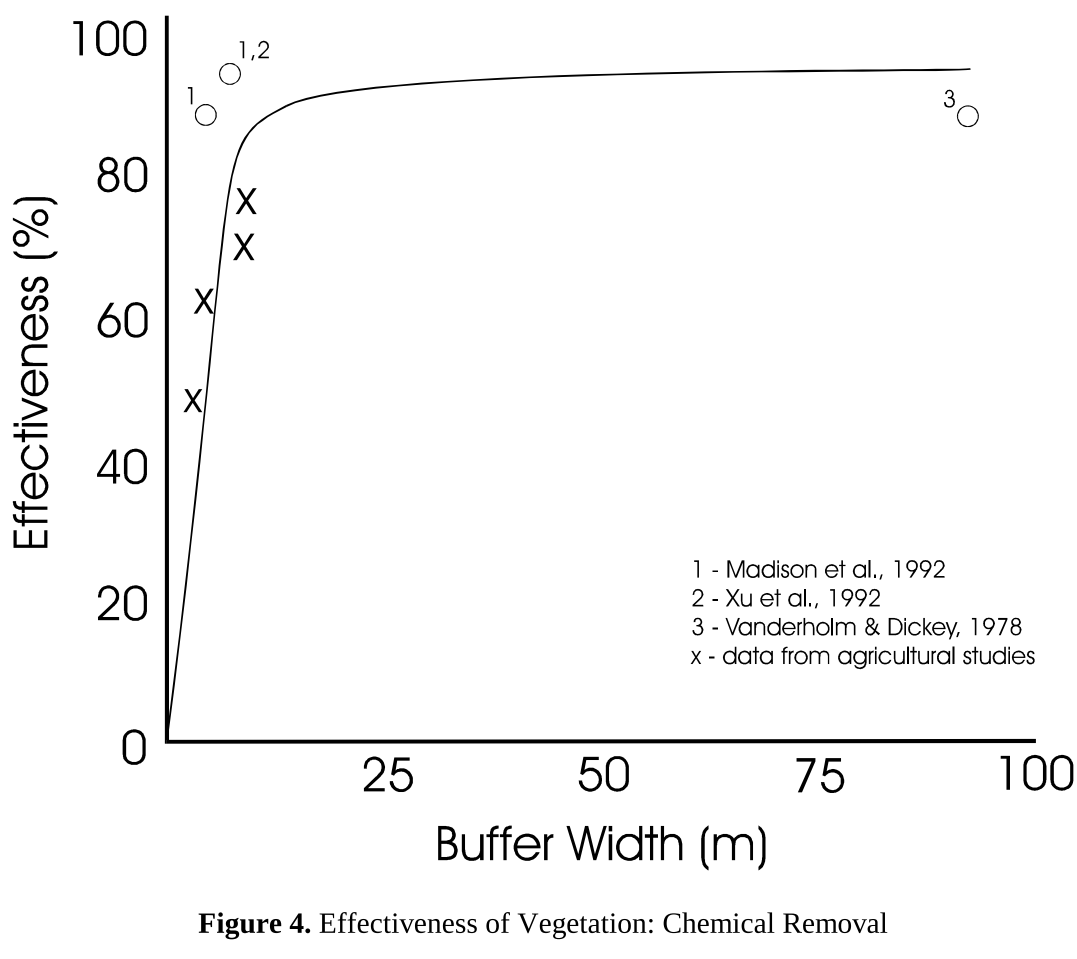


Figure 4. Effectiveness of Vegetation: Chemical Removal

Murdock and Capobianco (1979) found that *Glyceria grandis* took up 80% of the available P, and also took up significant quantities of Pb, Zn, and Cr. Gallagher and Kibbey (1980) found that other species accumulated Cu, Cr, Fe, Mn, Sr, Pb, and Zn. Hubbard and Lowrance (1992) noted the NO_3 had “very little impact” on riparian systems after passing through a 7 m forested buffer. They attributed the loss of NO_3 in the buffer to a combination of microbial denitrification and plant uptake.

Doyle, Stanton, and Wolf (1977) found that 3.8 m forested buffers and 4.0 m grass buffers reduced N, P, K, and fecal bacteria levels. Wooded riparian buffers in the Maryland coastal region were found to remove as much as 80% of excess P and 89% of excess N, most of it in the first 19 m (Shisler, Jordan, and Wargo 1987). Lynch, Corbett, and Mussallem (1985) evaluated the ability of vegetated buffers to reduce soluble nutrient levels in runoff from logging operations. They found that a 30 m buffer reduced nutrient levels in the water to “far below drinking water standards.”

Lastly, other pollutants which may be found in runoff in silvicultural areas–for example, in multiple-use areas managed by the USDA Forest Service, which may support both logging and livestock–include pesticides and fecal bacteria. However, Gilliam (1994) reported that “very little information is available at this time on removal of either of these contaminants.” Further, he noted that “researchers in Tifton, Georgia, and Auburn, Alabama, are measuring the removal of selected pesticides in riparian areas, and workers in Kentucky are investigating the removal of fecal bacteria.” Preliminary data of Coyne, Blevins, and Rhodes (1994) (reported in Gilliam 1994) indicate that fecal bacterial removal by riparian vegetation is highly variable.

Figure 4 presents a graphical representation of the effectiveness of buffer vegetation in removing chemicals prior to entry into streams. Note that the shape of this curve is similar to the shape of the curve in Figure 3. This is because nitrogen, phosphorus, heavy metals, and many organics–including synthetic organics such as pesticides–are strongly bound to sediment particles. Hence, the general trend depicted in Figure 4 reflects the removal of a significant amount of chemicals as sediments are removed from runoff.

However, the curve in Figure 4 is shown rising somewhat more steeply than that in Figure 3. This is because in addition to the relatively rapid removal of potential chemical pollutants bound to sediment particles, some chemicals, particularly nutrients, are readily taken up by vegetation, which removes chemicals from both runoff and groundwater (see discussion above). The forms of nutrients that are most readily available are typically dissolved and not bound to soil particles. The uptake of substantial amounts of these chemicals within a short distance, coupled with the rapid removal of some sediment-bound pollutants, results in a disproportionate amount of chemicals removed in the first few meters of a riparian buffer. Further, this curve flattens out after a short distance because, in runoff, the finest sediment particles and their pollutant load, plus chemicals that cannot be readily taken up or transformed within the buffer, would require long settling and residence times to be completely removed from runoff and groundwater.

5.0 SHADE PRODUCTION/TEMPERATURE MODERATION

The effects of altering streamside vegetation, particularly overhead canopy, have been the subject of considerable research and many reviews (Beschta et al. 1987; Patton 1973; Brown and Krygier 1970; Brown 1969; Brett 1956). Significant alteration to or removal of overhead canopy allows increased direct sunlight to reach the stream. Direct sunlight, especially in summer, can increase stream temperature and in turn affect fish and aquatic insect species’ composition and growth. High summer water temperatures can increase the virulence of many fish diseases, provide a habitat that favors less desirable fish, inhibit spawning activity or block spawning runs into streams, affect the quantity of food available, and alter the feeding activity and body metabolism of fish (Lantz 1971).

Many factors must be considered in defining minimum buffer widths to maintain water temperature. Sullivan et al. (1990) list the types of variables that are included in evaluating heat transfer in stream environments:

VARIABLE	EXAMPLE
Geographic	latitude, longitude, elevation
Climatic	air temperature, relative humidity, wind velocity
Stream Channel Characteristics	stream depth, width, and velocity; substrate composition
Riparian or Topographic Shading	sky view factor (% shade), canopy density, vegetation height, crown radius, topographic angle

Sullivan et al. (1990) also report that while there are many variables, analysis performed by Adams and Sullivan (1990) showed that four variables primarily regulate heat input and output to and from streams: riparian canopy, stream depth, air temperature, and groundwater inflow.

The amount and quality of light reaching streams are determined by forest vegetation height, forest canopy density, stream channel width, and channel orientation in relation to the sun's path in the sky (Naiman et al. 1992). Barton, Taylor, and Biette (1985) state that a minimum buffer width depends on the age and species composition of the riparian vegetation and its resulting height and foliage density. They further state that final refinements of estimates of rates of cooling (or warming) of streams entering (or leaving) buffer strips would have to consider such factors as total discharge, gradient, and groundwater discharge, because cooling (or warming) rates are a function of the time during which a given mass of water is shaded from (or exposed to) sunlight and the rate of dilution by cooler groundwater. From their research, Barton, Taylor, and Biette (1985) observed that the length of the buffer strip (i.e., distance upstream from a given site) is also an important factor in defining the effectiveness of the buffer strip.

Steinblums, Froehlich, and Lyons (1984), Hewlett and Fortson (1982), Brazier and Brown (1973), and, in particular, Beschta et al. (1987) comment on the effects of riparian vegetation on stream temperatures. Beschta et al. (1987) report that the relative degree of shading provided by a buffer strip depends on a range of factors (e.g., species composition, age of stand, density of vegetation). They state that buffer strips with widths of 30 m or more generally provide the same level of shading as that of an old-growth stand, while Corbett and Lynch (1985) conclude that a 12 m buffer may be adequate to protect streams from large temperature changes following logging.

Broderson (1973) found that 15 m buffers provided 85% of the maximum shade for small streams. Broderson found that buffer widths along slopes could decrease with increasing tree height. For instance, a stand 61 m tall on level ground provides shade approximately 27 m from the trunk during mid-July when temperature problems often occur. If this stand of trees were on a 60% slope, the effective shade width would increase to 46 m. In the summer months, shadow length also increases with increasing latitude. Lynch, Corbett, and Mussallem (1985) found that a 30 m buffer from logging operations maintained water temperatures within 1°C of their former average temperature.

Other researchers have demonstrated that buffer widths are not a good measure in controlling stream water temperatures. Brazier and Brown (1973) state that commercial timber volume and the width of the buffer strip are not important criteria. For the streams studied as part of their research, the maximum shading ability of the average buffer strip was reached within a width of 24 m. They found that the canopy density along the path of incoming solar radiation best describes the ability of the buffer strip to control stream temperature.

Steinblums, Froehlich, and Lyons (1984) reached a similar conclusion. In evaluating the survival and effectiveness of 40 streamside buffer strips in the Cascade Mountains of western Oregon, they found that stream shading was related to four characteristics of the buffer strip, and that survival was a function of seven vegetation and topographic variables. The authors define buffer strip effectiveness in terms of stream shading, which was also quantified by angular canopy density (ACD). Angular canopy density effectively integrates spatial factors such as stream width, tree height, and canopy density for a given site. The relationship of ACD to buffer strip width was curvilinear, yielding ACD values of 17 and 73%, respectively, for buffer widths of 6 and 31 m. They also concluded that 90% of the maximum ACD could be obtained with a 17 m buffer strip.

Figure 5 summarizes the recommendations and findings of the authors cited above. The shape of the resulting curve is dictated in large part by the limited data and the narrow range of the findings. The maximum shade production cited by six authors, for example, was achieved in 17 to 30 m of the stream channel. Except for Steinblums, Froehlich, and Lyons (1984), little data was cited for the effectiveness of buffers less than 10 m.

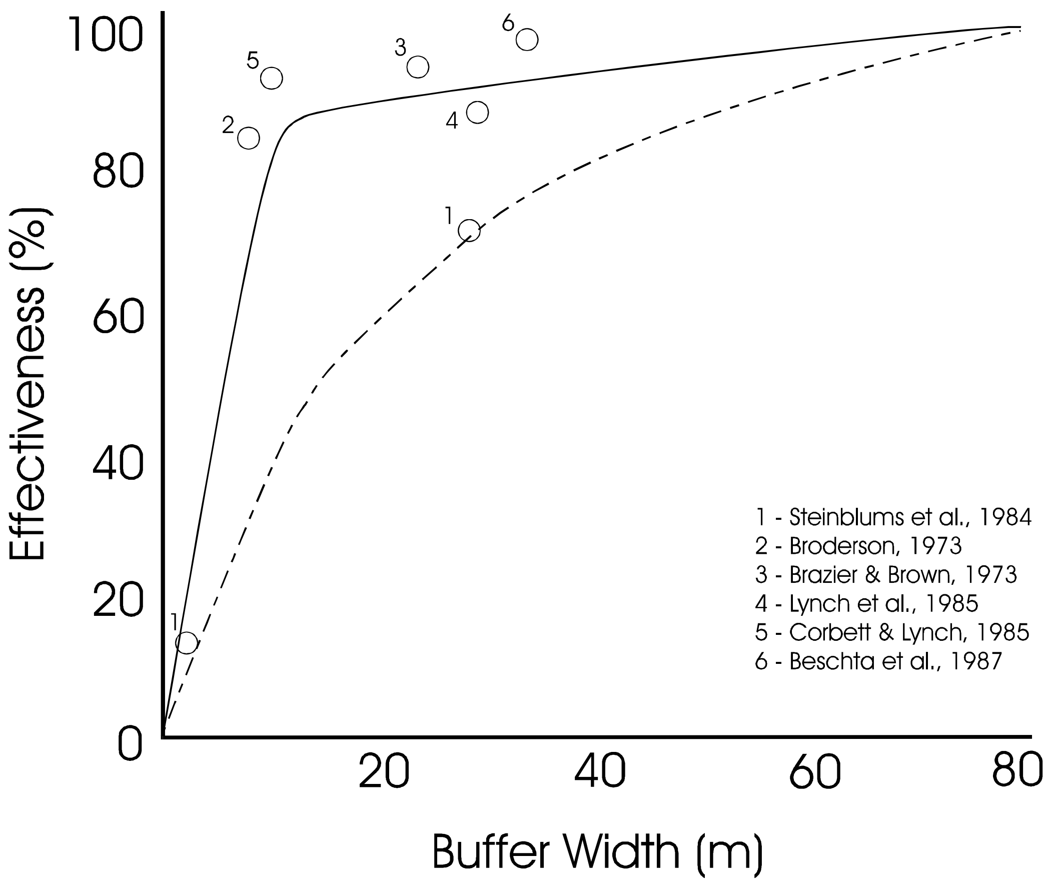


Figure 5. Effectiveness of Vegetation: Shade Production

6.0 LARGE WOODY DEBRIS

Large organic debris, sometimes known as either large woody debris (LWD) or coarse woody debris (CWD), is the principal factor determining the characteristics of aquatic habitats in low- and mid-order forested streams (Naiman et al. 1992). Numerous investigations have documented the importance of woody debris as instream structure and cover structures for fish such as salmonids; Bisson et al. (1987) provide a useful review of many of these studies.

Sedell and Beschta (1991) summarize the role of wood and snags in streams as (1) creating and maintaining pools, (2) causing local reductions in stream velocities that serve as foraging sites for fish feeding on drifting food items, (3) forming eddies where food organisms are concentrated, (4) supplying protection from predators, (5) providing shelter during winter high flows, and (6) trapping and storing organic inputs from streamside forests, enabling them to be processed biologically.

Sedell, Swanson, and Gregory (1984), citing seven authors, state that pristine streams and rivers in North America contained large quantities of downed trees. They state that the record consistently indicates that wood from downed trees was a dominant feature of streams, regardless of their location in North America. Most LOD from trees adjacent to a channel reach is probably delivered to that reach when live trees are felled by windthrow, bank cutting, or flooding (Van Sickle and Gregory 1990; Murphy and Koski 1989).

Darling et al. (1982) assessed an Oregon State University (OSU) formula for protecting streams and wetlands from tree blowdowns and subsequent large debris and sediment incursions into streams and wetlands. This formula includes factors such as slope, and horizontal and vertical distances from the midpoint of the buffer to the top of the nearest major ridge in the direction of the prevailing winds. Additionally, soil stability and antecedent soil moisture are considered. These investigators were primarily interested in buffer stability over time, and concluded that the OSU formula could be successfully applied in Olympic National Forest, Washington. They did not, however, directly address buffer widths.

Murphy and Koski (1989), in studying input and depletion of woody debris in Alaskan streams, found that almost all (99%) of identified sources of woody debris in streams 8 to 30 m in width were within 30 m of the stream bank. Nearly half of the woody debris came from trees that stood on the lower bank (less than l m away), and 95% was from trees within 20 m of the stream. They also noted that distances to the source of woody debris differed between channel types.

McDade et al. (1990) also studied the source distances of woody debris in 39 sites in western Oregon and Washington. Their analysis of old-growth conifer forests suggested that a 30 m wide buffer strip would provide 85% and a 10 m strip would supply less than half the amount of naturally occurring debris. Their research also suggests that tree height is a factor in recruiting woody debris, and that the number of debris pieces and source distance increased with bank slope.

Robison and Beschta (1990) used effective tree height as a measure of probable recruitment of woody debris. Effective tree height was defined as that part of the height of a tree that would provide woody debris of a minimum diameter to a stream. For example, if the minimum diameter needed is determined to be 10 inches, and a tree is 10 inches in diameter at 60 feet in height, the effective height is 60 feet. If a tree is more than one effective tree height away from the stream, the probability of contributing woody debris to the stream approached zero. A tree of sufficient diameter immediately adjacent to the stream has a 50% chance of contributing woody debris to the stream.

Van Sickle and Gregory (1990) also developed a model to predict inputs of woody debris to streams from falling trees. Their model contains 15 variables including effective tree height, riparian stand density, and downslope distance from the standing tree to the nearest channel boundary. The model also includes several probabilities such as the probability of the tree falling in a given time frame, the tree-fall angle, and the tree being delivered to the stream.

Van Sickle and Gregory (1990) explain that the mean total number of trees delivered to a stream is directly proportional to stand density, fall probability, and tree height. Any increase in these variables would result in an increase in the number of trees reaching the stream. The effective volume of wood delivered (expressed as per unit area of channel), however, is inversely related to stream width. For streams wider than one tree height, the total input from riparian areas remains constant, giving a hyperbolic decline in the input per unit area.

Van Sickle and Gregory (1990) further explain that much of the decrease in the amounts of *in situ* LOD in larger streams is also due to the relative importance of transport and input of these systems. Their model equations show that the number of trees is independent of stream width, i.e., identical riparian stands along a small stream and a large river may contribute the same number of LOD pieces per unit channel length. The decline in the number of pieces of resident LOD in large streams was due to the transport capacity of larger streams, rather than to changing LOD inputs.

Van Sickle and Gregory (1990) also discuss the importance of stand composition (mixed height vs. uniform height) and the effects of slope steepness on tree-fall direction in sizing riparian management zones. Trees entering the channel from a short distance contribute longer pieces with greater diameter, and thus greater volume, than do trees entering from a greater distance. They also found that the contributed volume of a mixed-height stand was greater than that of a uniform stand.

Finally, their model also implies that the contribution of trees far from the channel (but within one tree height) is relatively smaller in number and volume when the fall direction is random than compared with towards-channel falling. With a random fall, the probability of a tree being delivered to the stream decreases with increasing distance from the channel.

As can be seen from the discussion above, many factors contribute to the effectiveness of a riparian buffer in delivering LOD to a stream channel. Figure 6 summarizes the effectiveness of LOD production and recruitment, based on data from the authors cited. Figure 6 illustrates that 40 to 60% of the LOD input from an uncut riparian zone occurs from within approximately 10 m of the stream channel. Further, 80 to 100% of the LOD comes from within 20 to 30 m. It should be noted that the influence of the many physical factors (e.g., slope steepness or stream size) on LOD recruitment is not incorporated into the findings or recommendations cited in Figure 6.

7.0 PARTICULATE ORGANIC MATTER

The effectiveness of buffer strips on the aquatic food chain has been studied most frequently by contrasting the effects of timber harvest with and without buffer strips. Similar to Belt, O'Laughlin, and Merrill (1992), only a few studies where the characteristics of the buffer strip were related to food production were found.

Various types of organic matter and inorganic nutrients stored in or passing through the stream forms the basis of the food chain. Gregory et al. (1991) and Murphy and Meehan (1991) present thorough discussions of the ecosystem processes that underlie stream productivity. Energy becomes available to the stream community from two main sources: photosynthesis by aquatic plants in the stream itself (autochthonous sources) and decomposition of organic matter imported from outside the stream (allochthonous sources). The mix of energy sources has a major influence on the structure and function of stream ecosystems.

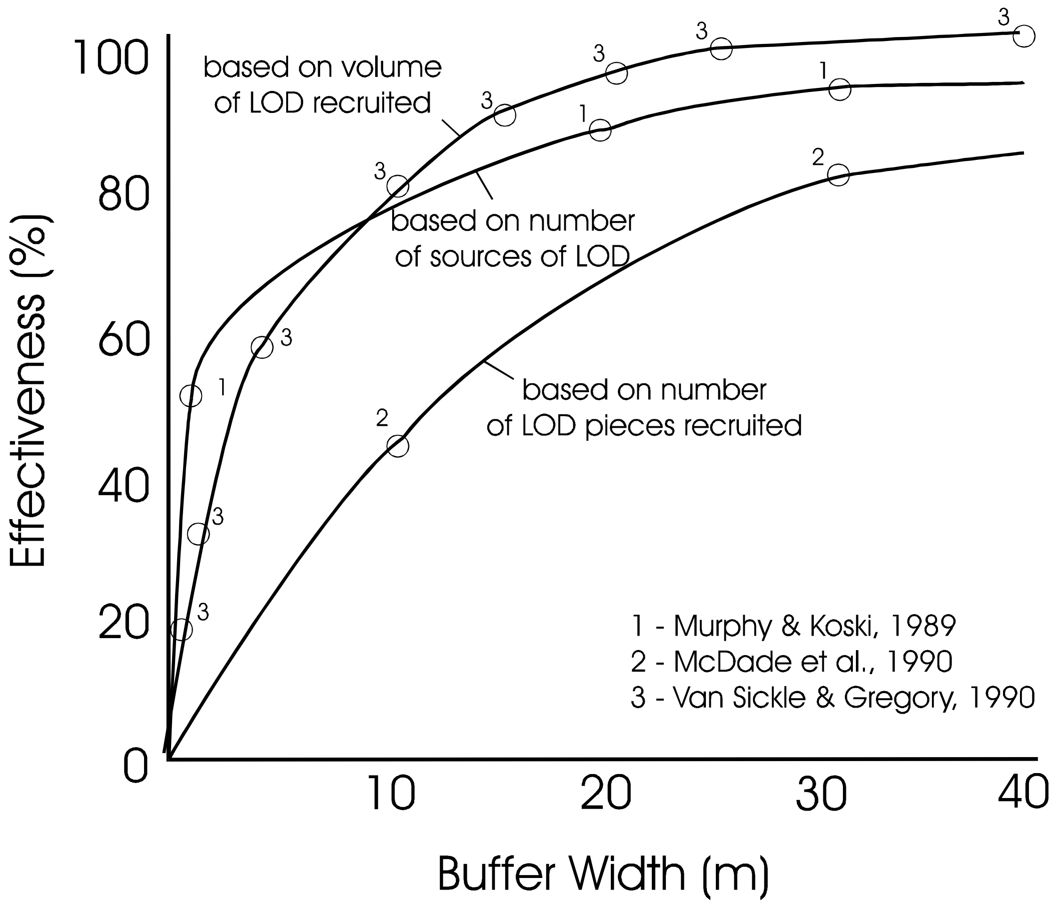


Figure 6. Effectiveness of Vegetation: LOD Production

Erman, Newbold, and Roby (1977), Roby, Erman, and Newbold (1977), Meehan, Swanson, and Sedell (1977), and Murphy and Meehan (1991) discuss the importance of overhead canopy shade and input of organic matter from the riparian zone to the aquatic and terrestrial invertebrate communities. Meehan, Swanson, and Sedell (1977) state that the food base for the biological communities of forest streams consists of leaves, needles, cones, twigs, wood, and bark. The insect communities that live on this plant material form a significant food component for trout and juvenile salmon.

As predators, stream dwelling juveniles of anadromous species and juvenile and adult phases of a number of resident fish are dependent on prey species directly linked to bacterial or vegetative food sources. Reiser and Bjornn (1979), Meehan, Swanson, and Sedell (1977), and Hynes (1970) stated that the most widespread and important foodstuff of running-water fishes is invertebrates. Stream fish eat a wide range of invertebrates. Generally, these fish feed on a variety of freshwater and terrestrial insects, oligochaetes, arachnids, and zooplankton (Higgs et al. 1995). During summer periods, 40 to 50% or more of the diet of stream-dwelling trout and juvenile salmon can consist of terrestrial insects (Hynes 1970). These insects usually enter streams by falling or being blown off riparian vegetation (Reiser and Bjornn 1979). When terrestrial insects become scarce during winter periods, trout feed almost exclusively on aquatic insects.

Bilby and Bisson (1992) state that the organic matter budgets of small streams flowing through forested watersheds are dominated by inputs of terrestrial material. They report (citing Gregory 1980) that the dominance of terrestrial matter is caused by high inputs of material from allochthonous sources coupled with suppression of autochthonous production by heavy shading from terrestrial vegetation. Annually, riparian forests add large amounts of leaves, cones, wood, and dissolved nutrients to low- and mid-order streams (Gregory et al. 1991). These organic inputs originate as particles falling directly from the forest into the stream channel (or moving downslope along the forest floor by wind- and water-driven erosion) and as dissolved materials in subsurface water flowing from the hyporheic zone (Naiman et al. 1992).

Bilby and Bisson (1992) also state that removal of riparian vegetation through timber harvest reverses the relative importance of allochthonous and autochthonous organic sources by stimulating primary production and decreasing inputs of terrestrial organic matter. Greater autochthonous production and decreased inputs of terrestrial materials influence consumer trophic levels within the stream (Murphy and Meehan 1991). According to Bilby and Bisson (1992), the invertebrates that consume autochthonous energy sources benefit from improved food resources when more sunlight reaches the stream channel, nutrient concentrations are elevated, and algal growth is stimulated. Because of this, overall invertebrate production and increased density, biomass, and production of salmonids in streams flowing through clear-cut areas have been documented. They also state that enhancement of food resources through forest canopy removal may in some cases be masked by degradation of other aspects of the stream environment.

In studying two adjacent reaches, Bilby and Bisson (1992) found that allochthonous input at the old-growth site (i.e., with an intact buffer) was approximately five-fold greater than at the clear-cut site (i.e., with no buffer). Organic matter from autochthonous production at the old-growth site was about 35% of the input from terrestrial vegetation. At the clear-cut site, autochthonous production contributed about three times the amount of organic matter that was delivered from the terrestrial system.

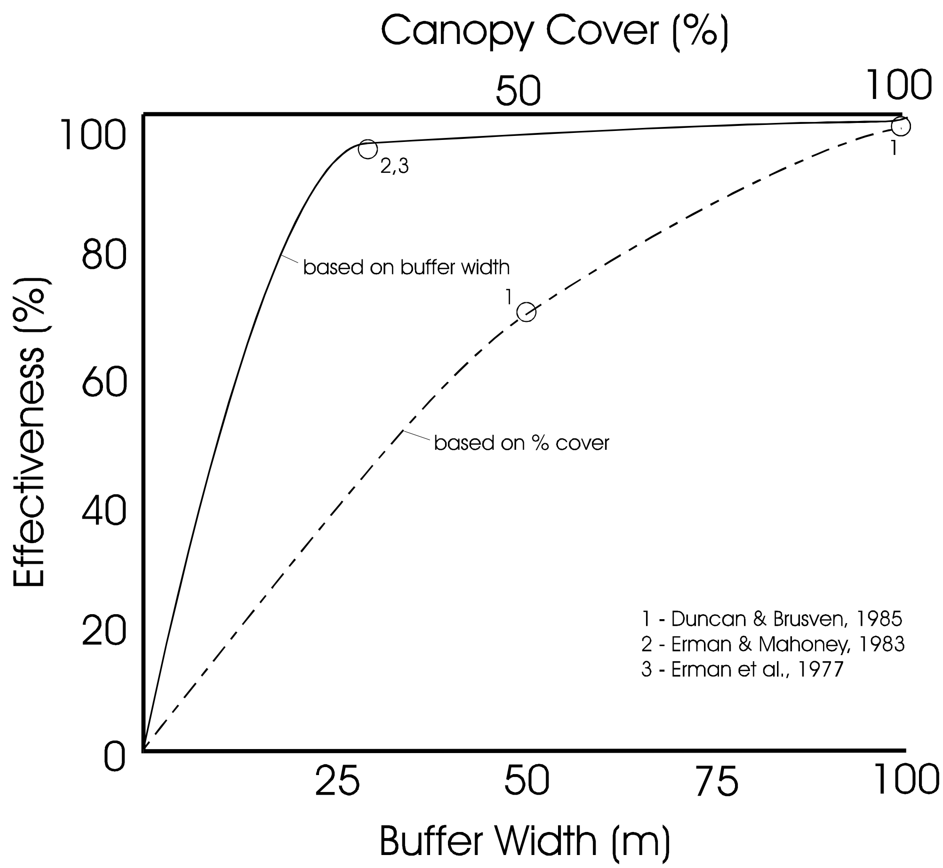
Culp and Davies (1983) found that although logging opened the forest canopy and increased the light available for primary production, algal biomass did not increase after logging because phosphorus remained the limiting factor. Allochthonous litter input to the stream was significantly reduced at both logged sites, but the site with a buffer zone provided greater amounts of leaf litter to the stream, and had a higher post-logging benthic standing crop than the site without a buffer zone. They also found that throughout the pre- and post-logging periods, seasonal changes in macroinvertebrate community composition were strongly affected by the seasonality of discharge. While the trophic composition of the macroinvertebrate communities was not affected, logging of the streambank significantly decreased macroinvertebrate densities in the winters, primarily because post-logging sedimentation increased winter scouring. Macroinvertebrate densities at the site without a buffer zone were also reduced in the summer and transitional periods because of sediment intrusion into the substrate and the reduced standing crop of detritus. Macroinvertebrate communities were less detrimentally affected by logging when a 10 m riparian buffer zone and natural debris dams were left along the stream. The buffer zone reduced logging-related scouring in the winter, and leaf litter input in the summer and the transitional period was more similar to pre-logging conditions.

Other studies indirectly relate food production to insect diversity or production. Murphy and Hall (1981), Murphy, Hawkins, and Anderson (1981), and Chapman and Knudsen (1980) have shown that the removal of canopy cover can increase primary production, resulting in an increase in the standing crop of macroinvertebrates and fish.

Erman, Newbold, and Roby (1977) found that buffer strips less than 30 m were ineffective as protective measures (defined as preventing significant changes in the invertebrate community). Buffer strips greater than 30 m afforded protection equivalent to conditions in unlogged streams.

Belt, O'Laughlin, and Merrill (1992) cite a study by Erman and Mahoney (1983) in which the effectiveness of buffer strips relative to food production in terms of rate of recovery of post-harvest macroinvertebrate diversity was compared with pre-harvest levels. The streams without buffer strips showed an increase in diversity but incomplete recovery after a six-year period. Streams with a 30 m buffer strip maintained diversity at a constant level.

In southwest Alaska, Duncan and Brusven (1985) developed a series of energy-flow models that related the percent coverage of riparian canopy to three biological production variables–invertebrates, potential salmonids, and useable allochthonous production. Their model for invertebrate production showed that reducing the canopy from 100 to 50% caused a 28% decrease in invertebrate production. Figure 7 presents a graphical representation of this relationship. Note that for purposes of preparing Figure 7, 100% cover was considered to be equivalent to 100% effectiveness; therefore, a reduction in cover to 50% results in an effectiveness of 72% (a 28% decrease).



Note: percent canopy cover is not related to buffer width; the two x-axes are shown on the same graph only to illustrate two ways of examining vegetation effectiveness on POM production.

Figure 7. Effectiveness of Vegetation: POM Production

8.0 ABIOTIC FACTORS

The previous discussion focused on the role of vegetation in maintaining stream integrity. However, numerous abiotic factors affect the biological, chemical, and physical characteristics of streams. In some instances, these factors may be as important as the vegetative conditions of a riparian zone. In addition to vegetative factors, Table 1 shows four other groups of factors which affect riparian function: local catchment, flow regime, stream parameters, and soil conditions.

Table 1. Factors Affecting Riparian Functions

FACTORS	FUNCTION					
	Shading	LOD	POM	Erosion	Sediments	Chemicals
Catchment						
size					x	x
topography	x	x	x			
slope gradient	x	x	x		x	x
slope length					x	x
geology				x	x	x
runoff					x	x
local climate	x	x	x			x
Flow Regime						
in-stream volume		x	x	x		
frequency		x	x	x		
duration	x	x	x	x		
inflow	x			x		x
Stream						
gradient	x	x	x	x		
width	x	x	x			
width:depth ratio	x	x	x	x		
aspect	x					
flood-prone width	x	x	x		x	x
degree constrained	x	x	x	x	x	x
Soil						
texture				x	x	x
structure				x	x	x
depth		x		x	x	x
CEC/AEC						x
fertility	x	x				x
moisture capacity	x	x		x		x
Vegetation						
stand type	x	x	x	x	x	x
tree type	x	x	x			
stand age	x	x	x	x	x	x
% canopy cover	x	x	x	x		
% ground cover			x	x	x	x
tree height	x	x	x			
buffer width	x	x	x		x	x
buffer length	x	x	x	x		
root abundance				x	x	x

As Table 1 illustrates, several factors appear to be important to most or all of the riparian functions considered in this paper. For example, non-vegetative factors such as side slope gradient, flood duration, flood-prone width, and the degree to which streams are constrained, appear to influence the broad range of riparian functions as much as vegetative factors such as stand type and age, and percent ground and canopy cover. Although a discussion of each of these abiotic factors is beyond the scope of this paper, the following side slope summary is an example of a non-vegetative consideration for inclusion in comprehensive buffer width formulations.

Several investigators recommend minimum buffer widths for areas with slopes less than 1%, along with additional distance for slopes ranging up to 70%. The recommended distance is based on adjacent land use, purpose of the buffer, and slope. The USDA Soil Conservation Service (1982), for example, recommends buffers of 3 to 8 m next to pastures with up to 30% slopes, 8 to 46 m near logging operations in areas of 0 to 70% slopes, and 23 to 92 m for livestock feedlots and liquid waste treatment on 2 to 6% slopes. Haussman and Pruett (1978) recommend buffers of at least 8 m plus an additional 0.6 m for each 1% of slope above streams, with a maximum of 50 m for slopes of 70%. Clark (1977) recommends buffers be a minimum 15 m plus 6 m for each 5 percent increase in slope.

Generally, buffer widths for streams may be established using two methods: a fixed width, or a variable width that considers specific site conditions. Examples of fixed-width buffers have been cited throughout this document. Investigators proposing methods for determining variable buffer widths using a variety of site factors include Groffman et al. (1990), Budd et al. (1987), Barton, Taylor, and Biette (1985), Roman and Good (1985), Steinblums, Froehlich, and Lyons (1984), and Darling et al. (1982). Fixed- and variable-width buffers each have advantages and disadvantages. Fixed-width buffers are more easily established, do not require regulatory personnel with specialized knowledge of ecological principles, and require smaller expenditures of both time and money to administer. This option, however, may result in arbitrary buffer distances that may not always be appropriate.

Depending on site conditions, a fixed width may not include essential components of the buffer, nor adequately buffer the riparian or stream system. In some instances, buffers may be larger than necessary to maintain riparian functions; when this occurs in silvicultural areas, for example, economic benefits are decreased. Naiman et al. (1992) state that simple prescriptive management, such as riparian zones of fixed width, is less effective than management techniques adapted to local topography and natural disturbance regimes. In other cases, again depending on site conditions and the riparian function to be maintained, a smaller buffer may adequately protect the stream and riparian community.

Variable-width buffers allow greater flexibility for varying site conditions and land management practices for landowners. Variable-width buffers can be tailored to existing site conditions and desired functions, eliminating the need to protect features non-existent in an area. The quality of buffer and site conditions (e.g., quality and age of vegetation, severity of impact, livestock density, or sensitivity of the system to disturbance) should be considered in determining a buffer width. This option may require that professional judgment be employed in the decision-making process, and thus, may not be feasible if experienced personnel are not available. Because of the variability of sites requiring buffers, individual site visits and detailed information are prerequisites for buffer-width decisions. While this is a more costly and time-consuming process, it may protect the environment more completely without causing undue losses to landowners.

9.0 FUTURE RIPARIAN BUFFER RESEARCH NEEDS

There is a large and growing body of literature regarding most of the six riparian functions covered in this report. The most notable exception appears to be streambank stability; information in this area is particularly lacking with respect to forested areas, since much of the most recent research focused on the effect of non-woody roots. Further, few studies of this function have been conducted in the Pacific Northwest.

Generally, there are two types of research needs. The first entails re-visiting some of the data generated by past studies that examined only one buffer size, but did not study the effects of increasing or decreasing the size of the buffer. Unfortunately, information from such studies may be construed by resource agencies and land managers as minimum guidelines. For example, if a study stated that a 30 m buffer adequately protected streams, it might be inferred that smaller buffers were studied. This might suggest that 30 m buffers should be a minimum standard width. However, if that study were re-visited using buffers of 5, 10, 15, and 20 m, it might be determined that somewhat smaller buffers may be as or nearly as effective, particularly for specific riparian functions (e.g., Figure 4). As an alternative to studying varying buffer widths, other buffer zone management practices should be investigated. For example, stand composition could be manipulated to favor tree species which provide exposed roots (for sediment trapping), high transpiration rates (for nutrient uptake), and broad canopies (for shade production).

The second type of needed research should focus on the interactions between vegetative and non-vegetative factors. Depending on site specifics and the nature and degree of potential impacts, it might be determined that abiotic factors are more important than vegetation in determining buffer effectiveness. These various factors can be isolated and studied in laboratory or other controlled settings, but in nature all biotic and abiotic factors work together, and isolating individual parameters provides insight into only artificial environments.

In both types of research, the focus should be on the physical, chemical, and biological *mechanisms* which are responsible for buffer effectiveness. Understanding why a particular buffer parameter has a certain effect will allow for more effective buffer management, which in turn will result in higher levels of stream protection and optimum timber yields.

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