Riparian Soils: A Literature Review

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Introduction

Definitions of what constitutes the riparian zone are numerous and varied. Although the boundaries of riparian ecosystem can be highly variable, in general they extend outward from the river or stream channel, include the limits of flooding, and travel into the canopy of streamside vegetation (Sedell et al. 1991). The riparian zone size is directly proportional to stream size and site topography; steep slopes characteristic of small streams may limit the development of riparian vegetation, while aquatic systems with less extreme topography exhibit larger riparian boundaries (Bilby 1988). Conversely, the influence of the riparian zone on the aquatic system decreases as stream size increases (Bilby 1988; Agee 1988).

Karen M. Manci (1989) defines the term "riparian ecosystem" as "landscapes adjacent to drainage ways of floodplains that exhibit vegetation, soil, and hydrologic mosaics along topographic and moisture gradients that are distinct from the predominant landscape surface types." Functionally, riparian zones can be defined as "3-dimensional zones of interaction between terrestrial and aquatic systems" (Sedell et al. 1991). In the Pacific Northwest this 3-dimensional zone comprises less than 5% of the total landscape (Sedell et al. 1991); riparian ecosystems make up 2 to 11% of the land in other regions (Oliver and Hinckley 1987).

Riparian zones are unique and dynamic systems. Major types of disturbance that impact these systems include management activities such as livestock grazing, timber harvest, recreational use, and the creation of physical structures like dams and roads, or natural perturbation such as fire, beavers, windthrow, and the action of water (Hall 1988). The effects of disturbance on riparian soils are variable. Anthropogenic disturbances tend to increase surface runoff in riparian systems, remove protective riparian vegetation, and alter the flow of water through aquatic systems (Manci 1989). In particular, impacts of livestock grazing on riparian soils include soil compaction, breakdown of undercut streambanks, and increased loss of sediment due to excessive removal of stabilizing vegetation. Timber harvest increases soil erosion and alters soil microclimates by increasing soil temperatures (Hall 1988).

Water

Of the various disturbances known to impact riparian forests, the effect of water is often the most variable and pronounced. The effect of water is variable both in the level of flow occurring throughout the year and in the impact of episodic 25-, 50-, and 100-year floods. In the Pacific Northwest, peak flows occur during the winter or early spring, and annual low flows occur during summer months of August and September (Hall 1988). Habitat disturbance by flooding increases the natural diversity of these ecotones, which are particularly adapted to these conditions (Raedeke 1988).

Standing water that is present during all or part of the year produces unique water and soil conditions in riparian zones, which results in plant communities that are distinct from upland habitats. The frequency and duration of flooding helps determine the distribution of riparian community types (Manci 1989), which often have a mosaic structure where small patches of distinctly wetland vegetation are mixed with elements of upland vegetation (Oliver and Hinckley 1987). Tolerance of particular species to soil and water conditions in the rooting zone influences the physiological impacts of changes in water level. The oxygen content, chemical composition, and nutrient availability of riparian soils influence how plants respond to flooded conditions; in addition, the impact of a specific water event is mediated by the age of vegetation, the time of year, and the sensitivity of a plant at a given time to damage by water (Manci 1989).

Upland and riparian soils are derived from different parent material due chiefly to the influence of water on riparian soils. While the parent material of upland soils is generally the rock that underlies the site, the mineral component of riparian soils originates as stream-deposited sediment. Thus, riparian soils are potentially more heterogeneous in mineral character than their upland counterparts. Periodic sediment deposition to riparian areas by streams during floods is accompanied by the flushing of organic litter from riparian sites by water. This increases the heterogeneity of riparian soils by producing a bare soil surface in some areas. This phenomenon also increases plant diversity in riparian zones by creating hospitable microenvironments for the seeds of species that require a bare soil surface for germination (Bilby 1988).

In addition to the redistribution of organic matter in riparian zones, the aquatic system further influences soil organic matter by increasing soil moisture. Riparian zones possess high levels of soil moisture due to both the presence of water in the stream and to the movement of groundwater into the rooting zone of riparian vegetation (Bilby 1988). Fluctuations in groundwater levels that influence the nature and extent of plant production and microbial activity are responsible for much of the variation in riparian zone soil, plant, and microbial properties. For example, as the water table approaches the surface and soils become more anaerobic, soil organic matter and denitrifier populations increase (Groffman et al. 1992). Wetter soil conditions also promote higher rates of decomposition where organic matter is present (Bilby 1988). On the other hand, high standing water tables may retard decomposition in some regions of the riparian zone if anaerobic conditions are present.

Geomorphic Processes

The term "sedimentation" encompasses three major processes of material transfer: erosion, transport, and deposition (Swanson et al. 1982). Sedimentation is an important process in riparian ecosystems, particularly for nutrient redistribution and export. Hillslope processes such as solution transport, litterfall, surface erosion, creep, root throw, debris avalanches, slump, and earthflow, are significant soil transfer processes that occur in riparian ecosystems. Swanson et al. (1982) define these process:

Solution transport results from leaching from vegetation, soil, and weathering bedrock or input from atmospheric sources and occurs in the dissolved state in subsurface water or, rarely, as overland flow. Litterfall is the transfer of organic matter as the final step in the sequence of events: nutrient uptake by roots, translocation to and incorporation in aboveground biomass, abscission or breakage, litterfall to the forest floor or stream. In steep terrain, downhill lean of large trees and canopy closure over small streams result in a net downslope displacement of organic matter.

Surface erosion is the particle-by-particle transfer of material over the ground surface by overland flow, raindrop impact, and ice- and snow-induced particle movement and dry ravel, which occurs during dry periods. *Creep* [continuous creep]…is slow, downslope deformation of soil and weathered bedrock…*Root throw* occurs as movement of organic and inorganic matter by the uprooting and downhill sliding of trees. *Debris avalanches* are rapid, shallow (generally one- to two-meter soil depth) soil mass movements. *Slump and earthflow* are slow, deep-seated (generally five-to ten-meter depth to failure plane) rotational (slump) and translational (earthflow) displacements or soil, rock, and covering vegetation.

Patterns of erosion and deposition create unique landforms that offer a variety of habitat opportunities for vegetation and microorganisms alike. Erosion also influences patterns of succession during or following disturbance on a local and regional level (Swanson et al. 1982). The soil surface processes that move seeds to and from sites may prevent or benefit seedling establishment at a site. Once established at a site, a seedling may be moved or removed by small or large-scale soil and debris movement or by catastrophic water events that erode streambanks and uproot or damage established vegetation. Sediment deposition may kill or suppress some vegetation by covering it, at the same time benefiting species that establish on bare mineral soil. The tipping and splitting of large trees due to geomorphic processes influence seeds and seedlings in a similar manner (Bilby 1988; Swanson 1980). The resulting soil conditions influence the rate of re-establishment, as well as the amount and types of vegetation that can establish a site.

Similarly, vegetation has an effect on soil transfer processes in riparian zones. Roots of riparian vegetation may impede streambank erosion by water, thus decreasing sediment inputs to streams and rivers. Inputs of organic material by riparian vegetation may form pools that reinforce channel structure and slow the movement of water. Large woody debris and standing trees may create a barrier to the movement of sediment and litter material, increasing the height of streambank terraces and decreasing the likelihood of flooding in these areas. Woody debris held 49% of the total amount of sediment stored in seven streams in Idaho, while the removal of woody debris from a stream in New Hampshire resulted in a seven-fold increase in particulate matter lost to the stream (Bilby 1988). Presence of vegetation also exerts a strong influence on nutrient cycling in riparian zones, which will be discussed later.

Geologic factors such as bedrock type and geomorphic constraints on soil accumulation, redistribution, and mixing exert a profound influence on soil properties. Landform effects on vegetation development vary according to microclimate, edaphic, and hydrologic factors at a site. Slope and aspect affect vegetation by microclimate. Slope steepness affects the soil erosion potential, texture and nutrient content. Steepness of slope and soil texture influences the soil drainage capacity. Landforms also influence vegetation by mediating the potential for disturbance at a site. The combined effect of landforms on soil formation, geomorphic processes, disturbance regime, and light, water, and nutrient availability at a site produces variations in the distribution of vegetation according to topographic position, slope, and aspect (Swanson 1980). For example, Beach (1999) found that Douglas-fir regeneration was positively associated with low terraces (1-3 m above bankfull width) and negatively associated with floodplains (<1 m above bankfull width) and hillslopes (slope > 20%), while western red cedar and western hemlock were both positively associated with high terraces (>3 m above bankfull width).

Coarse Woody Debris

The role of coarse woody debris is dependent on its decay status and physical distribution on the landscape. As log debris decomposes, the internal water and nitrogen content increase. This increase in internal moisture facilitates decomposition by preventing drying during warm, droughty summers typical of the Pacific Northwest. Barring geomorphic perturbation, CWD may remain permanently in place, with increasing contact with soil over time. Mycorrhizae that colonize decaying logs further enhance decomposition, carbon mineralization, and nitrogen immobilization and fixation, thus providing a potential nutrient source for colonizing Western hemlock seedlings, which, in turn, further fragment and aerate the CWD (Triska and Cromack 1980).

In the Pacific Northwest, decomposing woody debris functions as habitat for seedlings, particularly western hemlock, thus influencing plant succession (Triska and Cromack 1980). Beach (1999) observed that 52% of conifer regeneration occurred on CWD though CWD made up only 16% of the available rooting substrate. Sitka spruce, western red cedar and western hemlock seedlings were positively associated with CWD (Beach 1999). CWD also modifies the physical and chemical properties of the underlying soil. Soil under logs has been observed to increase in organic matter, microbial biomass, nematode density, root biomass and degree of nodulation, and calcium concentration. The amount of woody debris and its relative importance to forest and stream processes tends to increase as one travels upstream. Accumulations of woody debris modify stream channels and provide specialized habitat for insects, birds, mammals, fungi, and stream invertebrates. By slowing the flow of water, and increasing biologically and chemically active surface areas, coarse woody debris accumulations foster microbial colonization, consumption of organic particulates by invertebrates, and litter decomposition (Triska and Cromack 1980).

Decomposition of CWD generally takes several hundred years, although the size and species of debris influence its decay rate (Triska and Cromack 1980). Species of logs in order of decreasing longevity of same-size logs are western red cedar, Douglas-fir, western hemlock, and red alder (Agee 1988). Furthermore, a single log can exhibit various stages of decay, depending on site factors such as moisture, soil contact, and diameter of bole.

Litterfall and decomposition

Litter is particularly important in riparian zones because it is produced in higher quantities by riparian vegetation and has faster decomposition rates relative to drier upland regions. High rates of litter decomposition in riparian zones imply faster mineral cycling rates as well as higher proportions of bare soil. This favors primary production and plant colonization in later stages of decomposition (Xiong and Nilsson 1997). Drying and re-wetting events over short periods of time greatly influence nutrient release from decomposing leaf litter, although following the initial weathering period during which soluble nutrients are leached from fresh litter, decomposition is heavily influenced by microorganisms and soil invertebrates (Parkinson 1980). Litter decomposition is associated with invertebrate activity, which is second to moisture as the most important factor controlling decomposition in riparian soils. Soil animals, particularly macroinvertebrates, are generally more abundant and diverse in riparian than upland soils (Xiong and Nilsson 1997). Microbes also play a role in decomposition; specifically, fungi decompose aerated litter while bacteria process submerged litter.

High decomposition rates of standing dead and surface litter found in wetter forests tend to decrease with profile depth, while dry, exposed forest sites show low decomposition rates aboveground, with rates increasing with depth (Parkinson 1980). The decomposition of litter is influences by soil moisture conditions, as previously discussed, as well as the type of material deposited. Riparian vegetation in the Pacific Northwest tens to produce litter that is more easily and rapidly decomposed than litter from upland regions (Bilby 1988, Edmonds 1980). The combined effects of water and type of vegetation may result in riparian soils having very low levels of organic matter.

Riparian zones are also a source of litter to the streams and rivers they border. Connors and Naiman (1984) reported that lateral transport of litter to rivers was influenced more by the structure of vegetation and sediment obstacles than by stream size. They also found that direct litter fall from trees per unit of stream surface into streams declined exponentially with increasing stream order. Litter inputs to streams in riparian zones aids seed dispersal and primary production in stream ecosystems; litter is transported to and from riparian zones predominantly by flooding. Infrequent flooding has been found to increase litter production in riparian zones, while permanent flooding reduces litter production (Xiong and Nilsson 1997).

Nutrient dynamics

Accelerated decomposition rates result in rapid nutrient release to riparian soils (Edmonds 1980). The types and amounts of stream-deposited sediments also impact the chemical composition of riparian soils. When fish are present in streams, the decomposition of their carcasses may further increase the nutrient concentrations in riparian soils. Types and amounts of vegetation present in riparian zones affect nutrient cycling in these areas. Certain elements like phosphorus and nitrogen tend to be rapidly taken up and conserved by riparian vegetation, while others, like Ca, Cl, and Mg, show limited uptake by these plants (5-40% of total available) and are generally found in high concentrations in stream water (Bilby 1988). Some nutrients, like nitrate, exhibit seasonal fluctuations in concentrations in streams, indicating that uptake by plants may be limited to the growing season.

Carbon (C)

Some of the greatest increases in soil C occur in conjunction with N-fixing vegetation, which cause a 20-100% increase in soil C over their lifetime (Cole et al. 1995). Cole et al (1995) observed increases in C accumulation in the O horizon and mineral soil profile under red alder. In particular, the mineral soil C accumulation was 30%, and the O horizon C 200% higher under alder stands. Higher detrital production, lower decomposition rates, or both may account for these values.

Phosphorus (P)

Riparian ecosystems, because of their flatter slopes and high surface roughness, effectively reduce suspended soil particulates and, in doing so, often reduce phosphate concentrations in streams (Lyons et al. 1998; Amador 1997; Lowrance et al. 1984; Correll 1991). P retention in riparian soils is influenced by soil organic matter, pH, and Fe and Al content, and these factors exhibit spatial variability across a landscape (Lyons et al. 1998). Lyons et al. (1998) found that P retention capacities in riparian soils vary with drainage class, with moderately well drained and poorly drained soils having greater retention than somewhat poorly drained soil. In all cases, P retention appeared to be controlled by organic matter and Fe- and Al- oxides. In some regions, acidification by decomposition of organic matter and/or oxygen depletion may cause increased releases of P from riparian sediments (Pedrozo and Bonetto 1991).

Soil phophatases are common in riparian soils, as they are produced by plant roots, microorganisms, and earthworms. Phosphatase activity has been shown to vary seasonally and exhibit tremendous spatial variability in riparian soils; soil organic matter, pH, clay content, and the distribution of microorganisms, roots, and soil fauna in the soil contribute to the variability of phosphatase activity. Phosphatases are important in soils because these extracellular enzymes catalyze the hydrolysis of organic phosphate esters to orthophosphate; thus they form an important link between biologically unavailable and mineral P (Amador et al. 1997). Because phosphatase activity is sensitive to environmental perturbations such as organic amendments, waterlogging, compaction, fertilizer additions, tillage, heavy metal inputs, and pesticides, it is often used as an environmental indicator of soil quality in riparian ecosystems.

Amador et al. (1997) found that phosphatase activity was highest in poorly drained soil, and decreased as drainage improved. In general, spatial distribution of phosphatase activity in riparian soils was partly controlled by position in the landscape, with activity showing positive linear correlation with soil organic matter and moisture. Activity increased as root mass increased within the soil fraction. Other studies have shown increases in activity with soil pH in moderately well drained soil, with maximal activity occurring at a pH between 6.5 and 6.9 (Amador et al. 1997).

Nitrogen (N)

Some riparian zones have the ability to retain large amounts of N. Groffman et al. (1992) found that plant uptake was the dominant sink for nitrate during the growing season in riparian soils. The ability of a riparian zone to remove large quantities of nitrate from water or soil is influenced by the type and quantity of existing vegetation and by soil conditions (Ashby et al. 1998; Jordan et al. 1998; Correll 1991). Riparian zones contain potential hotspots of denitrification due to the presence of high water tables that may produce the anoxic conditions required for the process to occur (Hill 1996; Bilby 1988). Lowrance et al. (1984) observed a 31.5 kg/ha/yr loss of nitrogen from the riparian zone, reducing the N export by the watershed to 13.0 kg/ha/yr.

Denitrifiers are heterotrophic, facultative, anaerobic bacteria that use nitrate as an electron acceptor only when oxygen is absent (Hill 1998). Denitrification rates vary with soil organic matter, total P, temperature, and water-filled pore space; Ashby et al. (1998) found that denitrification increased with high soil organic matter, total P, and soil moisture. Rates were highest in wetter soils, and increased with soil ammonium and pH (Ashby et al. 1998). Groffman et al. (1992) found that denitrification enzyme activity (DEA) in surface soils was higher in wetland (poorly and very poorly drained) soils than in upland-wetland transition zone soils (moderately well and somewhat poorly drained). This was attributed to the presence of anaerobic soil conditions and higher levels of organic C in wetland soils. Ashby et al (1998) found that rate of nitrate supply to riparian soils and lack of available carbon limits denitrification in Catskill Mountain riparian forests: where carbon was readily available and soils were wet, rates of nitrate supply were more important than nitrate concentrations in soils. High pH and available P also promoted denitrification if C and nitrate were available and the soil was wet. Rates of denitrification are high in surface soils when organic matter and nitrate are high in riparian soils (Ashby et al. 1998; Jordan et al. 1998; Hill 1996).

Patches function as hotspots of denitrification in the soil when optimal conditions are met (Addy et al. 1999). The heterogeneity of denitrification in riparian soils is due largely to conditions within microzones. One study found that 25 to 85% of the denitrification generated from 98 g soil cores was derived from less than 1% of the sample (Gold et al. 1998). When anaerobic conditions, nitrate, and other conditions described previously are present in these microzones denitrification can occur, but absence of one or more of these prerequisites prevents denitrification (Jordan et al. 1998). Jacinthe et al. (1998) found that patches of decomposing roots were the most biologically active zone of N transformations in the riparian soil subsurface, likely due to sources of C to denitrifying bacteria.

During the winter dormant period, plant uptake is generally very low or nonexistent in riparian zones. Haycock and Pinay (1993) found that contributions of above ground biomass to soil C levels benefits soil microbes that reduce nitrate during winter months. During this period, nitrate retention in riparian soils is directly correlated with input loads (Haycock and Pinay 1993). Jordan et al. (1998) found rapid responses of denitrifiers to treatments with water, nitrate, and sucrose additions, concluding that denitrifying bacteria have a stock of enzymes poised to opportunistically exploit quickly changing soil conditions. High rates of groundwater nitrate removal from riparian forests during the dormant season indicate that microbial processes such as immobilization and denitrification are more important mechanisms of N removal than plant uptake during this time (Nelson et al. 1995; Simmons et al. 1992).

High concentrations of nitrate-N in groundwater were found to impact belowground processes in Maryland riparian forests. Increases in the consumption of forest-produced organic matter were observed, as well as the consumption of all available dissolved oxygen in the groundwater, the depletion of most of the nitrate --25% via assimilation and storage and the remainder via denitrification, and some available sulfate (Correll 1991). The removal of nitrate in groundwater requires that the nitrate first reach the soil surface (Jordan et al. 1998). This can occur after heavy rain, or by deep root transport and deposition by leaf leachate onto surface soils. Most riparian zones that remove groundwater nitrate have impermeable layers near the soil surface, which increases water residence time as well as increasing contact of water with plant roots and organic matter in riparian soils (Gold et al 1998; Hill 1996).

Red Alder

Red alder is commonly found in the riparian zones of the Pacific Northwest. Human influences on riparian ecosystems, including road building and timber harvest, promote invasion of riparian systems by invasive species like red alder. In addition to degree of scarification, density of alder regeneration at a site is related to the duration of summer drought. The roots of red alder are commonly invaded by an actinomycete that fixes atmospheric nitrogen into the soil, resulting in nitrogen levels 1.5-3 times higher than commonly found in stands of western hemlock, Douglas-fir, or Pacific silver-fir (Luken and Fonda 1983; Edmonds 1980). Dense red alder stands of 20 year-old trees were found to fix N at about 320 kg/ha on N-deficient soils (Newton 1968).

Presence of litter or other organic material on the soil surface often creates microenvironments more droughty than red alder can handle (Newton 1968). This can kill red alder, because heavy sedimentation can create oxygen deficits in buried roots (Oliver and Hinckley 1987).

Red alder litter contains about 2% N (dry weight), while other deciduous or coniferous litter contains merely 0.5 to 1% N (Swanson 1982b). Total aboveground litter was found to be about 2.6 times higher under red alder stands than under Douglas-fir (Cole et al. 1995). The litter of red alder was observed to release 33% of its nitrogen over two years, compared to a 12% loss from Douglas-fir litter (Edmonds 1980). In red alder stands, leaf decay was found to enrich the upper 15 cm of soil, while root decay enriched the lower soil layers during the early stage of alder dominance (Luken and Fonda 1983). Swanston and Myrold (1997) found that after 21 months of decomposition in a recent clearcut, alder detritus was a net source of N; most of the N remained in the upper 5 cm of soil where it was concentrated in labile soil N pools and some was incorporated in plant tissues. The combination of these two process have been shown to produce higher N levels in riparian litter and soil and much faster rates of nutrient cycling than in adjacent upland stands (Bilby 1988; Swanson 1982b). Luken and Fonda (1983) found that red alder communities established on bare sandbars increased soil N from 783 kg/ha to 3594 kg/ha, with trees holding 942 kg/ha. In these stands organic matter, moisture retention, and percent nitrogen steadily increased over time. The high nutrient content of red alder litter influences its rate of decomposition. Microbial litter processing is generally limited by the N-content of organic matter; thus, the high N-content of alder litter results in faster turnover rates for this material (Swanson 1982b). However, Cole et al. observed that initial rapid decomposition rates of red alder litter are followed by slower decomposition after 2 years. Over longer periods of decomposition, the higher concentration of N in alder litter may inhibit rather than promote mass loss. In addition, the wet and cold conditions under red alder stands during the winter months and the drier conditions during the summer may also impede decomposition at these sites. N-fixing alders cause significant and rapid changes to other soil properties such as decreasing soil pH, increasing levels of exchangeable Al, and decreasing P availability (Cole et al. 1995).

Nitrogen released from riparian soils through decomposition or leaching has the potential to impact aquatic systems. Litter with a high N content is quickly colonized and decomposed by microbes, providing a food source for stream invertebrates and a nutrient source for aquatic plants (Bilby 1988).

Conclusions

A variety of factors: water, geomorphic processes, and other disturbances, coarse woody debris, litterfall, and decomposition, and cycling of nutrients like C, N, and P contribute to the heterogeneity of soil and plant attributes in riparian zones. Much information is currently available about aboveground processes in riparian regions, such as plant succession, competition, and response to disturbance, but very little information exists regarding riparian soils. Future research in riparian areas should continue to focus on belowground processes like nutrient cycling and decomposition, as well as gaining new information about soil microbial biomass and soil microorganism populations and their role in soil processes.

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