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Scientific Literature Review of Forest Management Effects on Riparian Functions for Anadromous Salmonids

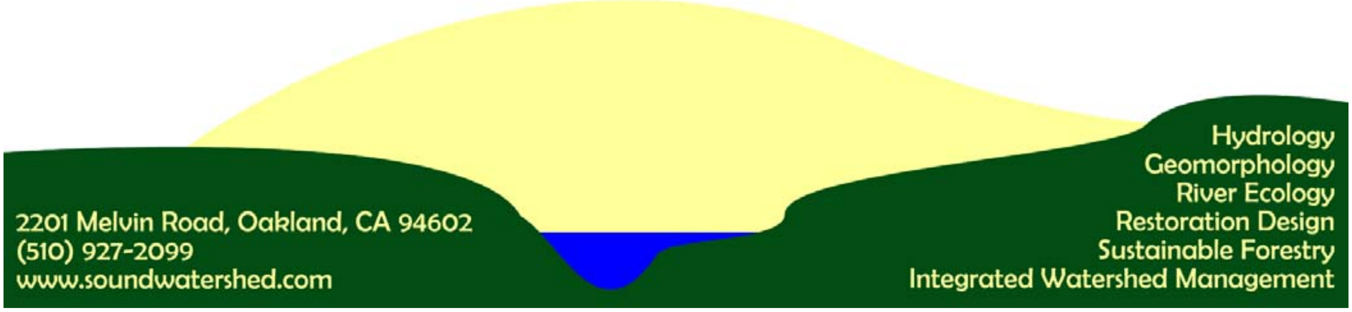
Chapter 2

BIOTIC & NUTRIENTS

for

The California State Board of
Forestry and Fire Protection

September 2008



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2) BIOTIC & NUTRIENT EXCHANGE FUNCTIONS

Scientific Literature Review of Forest Management Effects on Riparian Functions for Anadromous Salmonids

For

The California State Board of Forestry and Fire Protection

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September 2008

SWC Ref# 1013

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SUMMARY OF TABLES & FIGURES

EXECUTIVE SUMMARY

This document represents a comprehensive review of 31 scientific literature articles provided by the Board of Forestry to address a series of Key Questions relevant to riparian management for the protection of threatened and impaired watersheds in State and private forestlands in California. The review:

- summarizes recognized exchange function roles and processes as presented to us by the California Board of Forestry Technical Advisory Committee (CBOF-TAC 2007b)
- responds to key questions posed by the Board
- describes key information gaps not covered within the reviewed literature
- discusses inferences for forest management to address biotic and nutrient exchange functions

The literature on biotic and nutrient exchange tells us that litter produced in the riparian zone is an important food source for benthic macroinvertebrates , and thus indirectly supports salmonid production. But the quality of litter—its nutrient content and decomposition rate—are as important as the quantity of litter production. Alder produces “fast” (easily decomposed) litter that is rich in nitrogen; maple, willow and cottonwood produce litter of intermediate quality; conifers and oaks produce litter of lower quality and greater resistance to microbial decomposition. The timing of the life cycles of some benthic macroinvertebrates is thought to be synchronized with the production of different litter types.

Alder is not only beneficial to benthic macroinvertebrates, but supports a rich supply of terrestrial insects that fall into a stream from the riparian zone.

Opening the canopy cover over a stream and increasing light intensity has lead in many cases to increased primary (algae growth) and secondary (benthic macroinvertebrate) productivity, which is often beneficial to fish growth and production. In some cases, depending in part on nutrient supply, increased light can shift the dominant algae from diatoms to filamentous green algae, which are less desirable for macroinvertebrates and thus for fish. In opening the canopy over a stream there may be a trade-off between increasing aquatic productivity, which is beneficial to fish, and increasing water temperature, which may be detrimental to fish (see heat chapter)

Small floods increase the supply of food for salmonids by both washing food into the stream, and making flooded areas temporarily accessible for foraging (see water chapter).

A 30 meter wide buffer strip on both sides of a stream (with both equipment exclusion and no tree removal) generally reduces local impacts to a stream that are similar to a “no harvest” level. Completely excluding vegetation management in the buffer strip, however, may forego opportunities to increase fish growth rate and biomass, and to reduce fuel loads.

Topography, geomorphology, regional geography, and associated disturbance regimes strongly influence the vegetative characteristics of riparian zones. The shape and type of these natural landforms may be helpful in guiding buffer configurations including widths and other characteristics (e.g. structure, orientation, density, etc).

The literature suggests that active riparian management could benefit aquatic productivity with silvicultural prescriptions that are designed to enhance temperature regimes, aquatic primary productivity, woody debris recruitment, and reducing fuel loads. These prescriptions could continue to protect streams from known impacts (e.g., erosion from heavy equipment, excessive shade loss), by strategically locating management activities and sizing treated areas to prevent damage yet promote favorable biotic responses. The timing of such riparian management activities could also be scheduled to reduce risk and optimize favorable riparian stand characteristics across a stream network.

RECOGNIZED EXCHANGE FUNCTION ROLES & PROCESSES

The vegetation of riparian zones in forested environments regulates the flow of organic and inorganic nutrients, radiant energy and heat to the aquatic environment. These fluxes of nutrients and energy have major effects on the production of salmonids and other aquatic organisms. Some important principles to consider in understanding the biotic and nutrient exchange function are:

- Primary productivity in streams may be limited by nitrogen, phosphorus or light. In streams of north coastal California and in Oregon, nitrogen is often limiting, though elsewhere phosphorus may be more important (Allan, 1995). Gregory (1979) showed that light was limiting in Oregon streams, even at trace nutrient concentrations of nitrogen and phosphorous.

- Opening the riparian canopy may increase primary productivity, and biomass and diversity of aquatic invertebrates, and biomass of fish (Kiffney and Roni, 2007; Danehy et al, 2007; Bottorff and Knight, 1996).

- Increased light sometimes stimulates growth of filamentous green algae, which may be less palatable to some aquatic invertebrates than diatoms (Shortreed and Stockner, 1983).

The quality of riparian litter determines its susceptibility to decomposition and its availability to aquatic invertebrates. Alder litter is the most available and nutritious, followed by litter of other deciduous species. Conifer litter is generally less available and more difficult to process (Allan, 1995; Cummins 2002).

- In small fish-bearing streams, terrestrial invertebrates account for about half of the diet of salmonids during the summer and early fall (Wipfli, 1997; Allan et al., 2003)

- Biotic productivity in streams with conifer-dominated buffer strips that are wider than about 30 m (100 ft) is similar to that observed in an unlogged forest (Newbold et al. 1980, Castelle and Johnson 2000, Moldenke & Ver Linden 2007). Riparian stands dominated by deciduous vegetation (overstory and understory) within 10 to 20 m (33 to 65 ft) of the stream may increase biomass of consumers, including fish, as a result of nutritious litter inputs and terrestrial invertebrate subsidy (Allan et al. 2003, Richardson et al. 2004, Wipfli & Musselwhite 2004, Hoover et al. 2007).

RESPONSES TO KEY QUESTIONS

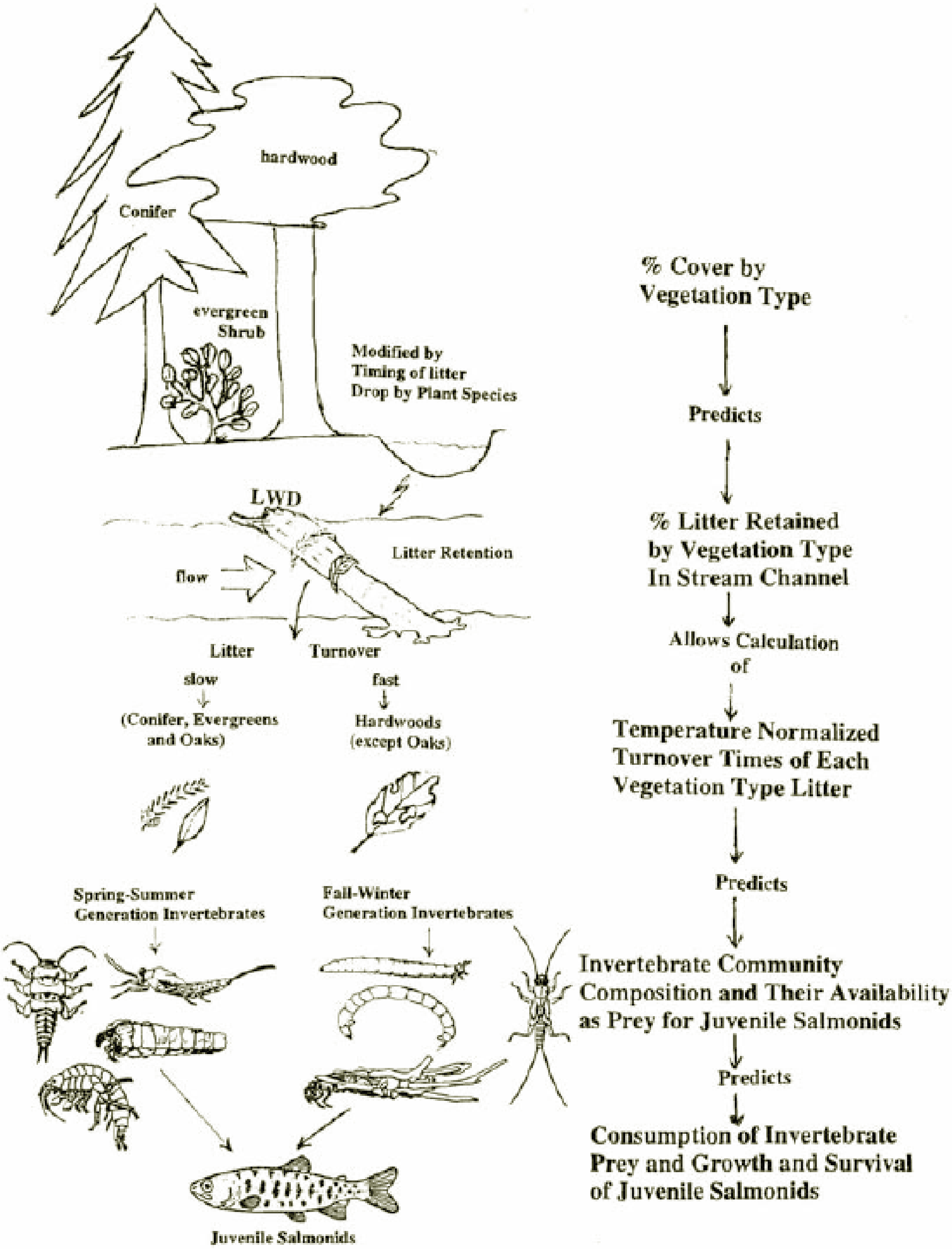
1. How can management (manipulation) of the riparian area lead to the establishment and maintenance of algal stream communities most beneficial to juvenile salmonids?

In a study in Carnation Creek, B.C., Shortreed and Stockner (1983) found that logging without protection of the riparian zone increased patchy accumulations of filamentous green algae, although these accumulations were not reflected in chlorophyll samples from artificial substrates. Nutrient addition experiments in Carnation Creek increased the abundance of filamentous green algae under low light conditions, indicating that phosphorus concentrations were the factor limiting primary productivity. Following logging, the increased light intensity and nitrogen concentrations had little effect on the periphyton community because logging did not increase P concentrations, except sporadically during high flow events. Shortreed and Stockner note that some streams in Oregon have shown an increase in filamentous green algae following logging, although diatoms frequently remain the dominant algal form.

In a study in the Oregon Coast Range, Danehy et al. (2007) found that diatom assemblages dominated sampled streams in clearcuts, thinned and old-growth stands, with substrate the most important variable influencing assemblage characteristics. Clearcut sites had higher invertebrate abundance, more Chironomid taxa, and higher invertebrate biomass than the thinned or uncut sites. There was no shift from diatoms to filamentous green algae.

Periphyton assemblages in streams change seasonally and are influenced by water velocity (Murphy and Meehan 1991). Diatoms dominate in areas of high velocity and peak production generally occurs in spring before riparian leaf-out and in autumn after leaf-off. Filamentous algae occur in low velocity areas and biomass generally peaks in spring and early summer. Filamentous algae may accumulate during the summer low-flow period when velocity declines and is washed downstream with the onset of increased flows in fall. These velocity related distributions for periphyton probably influenced the algal assemblage responses that were observed by the logging related studies. Flow strongly influenced algal biomass in Carnation Creek and the summer low-flow period delineated the algal growing season. Scour from frequent freshets throughout the rest of the year caused uniformly low accumulations of periphyton.

Figure 1. Riparian biotic and nutrient transfers and exchanges process relative to growth and survival of juvenile salmonids (CBOF-TAC 2007)



However, it does not appear that maintaining a closed canopy will maximize the productivity of juvenile salmonids. In streams in the Smith and Klamath River basins, Wilzbach et al. (2005) experimentally removed riparian tree canopy and added salmon carcasses in a factorial experiment to determine the relative effects of increased light and nutrients on density and biomass of rainbow and cutthroat trout. They found that increased exposure of the streams was very effective in increasing fish productivity, whereas carcass addition was not, and that increased primary productivity “appears to be the most important trophic pathway for increasing the availability of aquatic macroinvertebrates preferred by salmonids during spring and summer.”

Modenke and Ver Linden (2007) found that canopy removal increased the biomass and density of certain types of aquatic macroinvertebrates. They (like Nakano and Murakami, 2001) emphasized the importance of the emerging insects not just to fish but also to terrestrial predators. Kiffney and Roni (2007) found that light intensity at the stream surface and its interaction with other physical variables were important factors in explaining the variance in aquatic invertebrates species richness and biomass, and in fish biomass, although they did not measure the inputs of organic matter and terrestrial insects from outside the stream environment.

In a study of the effects of clearcut logging on stream biota at Caspar Creek (Jackson State Demonstration Forest, CA), Bottorff and Knight (1996) found increased chlorophyll-a and algal biomass; doubling of alder leaf decay rate for 2 yrs; increased macroinvertebrate density and diversity, EPT density and diversity, and chironomid density. They suspect that these changes were a result of changes in light conditions and possibly changes in nutrients or temperature. The North Fork Caspar Creek study area was protected by a riparian buffer zone that was 30 to 60 m wide with selective tree harvest in the outer portion of the zone. Post-harvest windthrow also reduce riparian stand density (4-30 % mortality; Reid and Hilton 1998).

A. WHAT RIPARIAN STAND CHARACTERISTICS ARE MOST LIKELY TO PRODUCE LIGHT AND NUTRIENT CONDITIONS THAT FAVOR A PERIPHYTON COVER DOMINATED BY DIATOMS AND SINGLE-CELL OR SMALL COLONY GREEN ALGAE BUT WILL AVOID (THAT IS, REMAIN BELOW THE THRESHOLD FOR) A COMMUNITY SHIFT TO FILAMENTOUS ALGAL FORMS?

Maintaining a vegetated riparian corridor with exchange between surface flow and the hyporheos will help to maintain dissolved nitrogen concentrations below levels that are likely to stimulate filamentous green algae (Poor and McDonnell, 2007). Thus it appears that the best way to avoid a shift from diatoms to filamentous green algae in a stream following timber harvest is to maintain an intact riparian corridor that:

1. maintains moderate to low light intensities on the water surface;
2. maintains a strong exchange of surface flow with the hyporheic zone;
3. limits introduction of phosphorous into the riparian environment;
4. limits deposits of fine sediment that form a medium for vascular plants within the active stream zone.

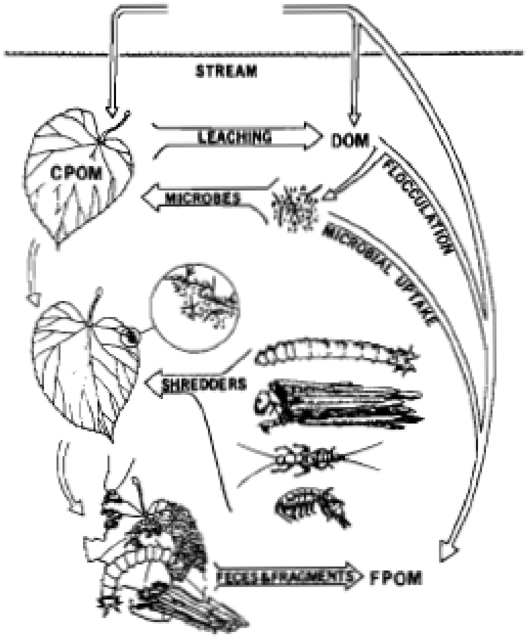
Kiffney and Roni (2007) suggest that supporting biological productivity is essential, and perhaps more important than maintaining physical exchange functions. Several studies suggest selective thinning of the riparian canopy as a way to increase aquatic macroinvertebrate production and thus food availability for salmonids (Wilzbach et al. 2005; Kiffney and Roni 2007; Modenke and Ver Linden 2007) The riparian stand characteristics most likely to achieve these functions would include:

1. a sufficient number of nitrogen-fixing deciduous trees distributed at key locations within the stream network;
2. a sufficient number of riparian canopy gaps that support primary and aquatic macroinvertebrate production while balancing effects on other riparian functions.

2/3. How can management (manipulation) of the riparian area lead to rapid processing (turnover) of riparian litter in the stream and a mix of litter inputs that favors the components of invertebrate prey organisms to yield higher growth rates and densities of juvenile salmonids?

Before litter derived from outside of stream can be processed by aquatic invertebrates, it must undergo the initial stages of breakdown and decomposition. These include leaching loss of dissolved organic and ionic material, and colonization by bacteria and fungi. Litter can be classified as fast, medium and slow, depending on the relative rate of the initial breakdown (CBOF TAC 2007). Alder and basswood produce fast litter, maples and hickory produce medium litter, and most conifers, oaks and ericaceous shrubs produce slow litter (Cummins, 2002). Alder litter is enriched in nitrogen because it has symbiotic root nodules that fix atmospheric nitrogen. As with the decomposition of litter on the forest floor, the nutrient content (especially the carbon:nitrogen ratio) is a key variable. Where the C:N ratio is wide, the initial microbial attack on cellulose is limited by the supply of readily-available nitrogen. Lignin, tannin and hydrophobic substances may also play a role is slowing the decomposition of conifer and ericaceous litter. Fungal species composition and richness in headwater streams are strongly influenced by both species composition of riparian vegetation, and by water chemistry (Meyer et al. 2007).

Figure 2. The sequence of litter fall (represented by a leaf) into a stream through leaching of dissolved organic matter (DOM), microbial colonization (especially by aquatic hyphomycete fungi), and shredder feeding on the conditioned leaf litter (Cummins 2002).

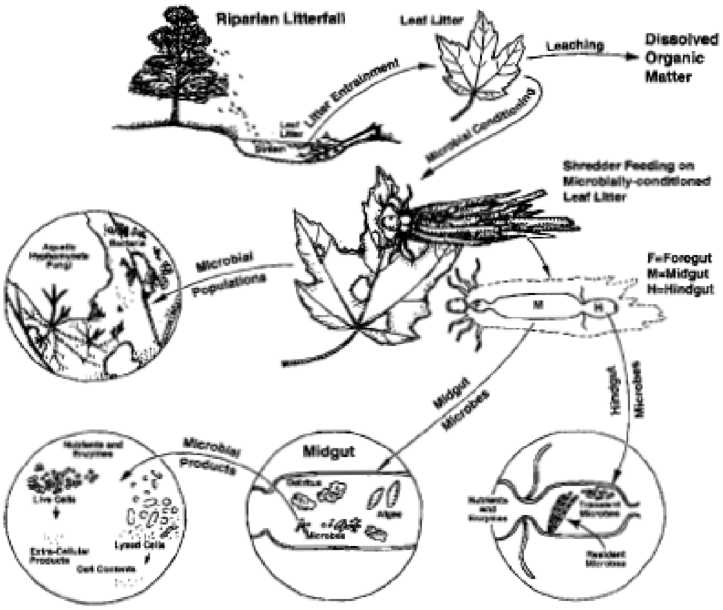


Richardson et al. (2004) measured the rates of breakdown and invertebrate colonization of western red cedar, western hemlock and red alder litter in a small coastal rainforest stream in British Colombia. They found that alder litter, with an N concentration nearly twice that of the conifer litter, lost mass 40-100% faster. During summer, hemlock lost mass faster than cedar, but in autumn the reverse was true. There were no differences between litter types in density of invertebrates per gram of leaf tissue, although alder litter consistently had higher numbers.

A. WHAT RIPARIAN VEGETATION STAND CHARACTERISTICS ARE MOST LIKELY TO PRODUCE NUTRIENT CONDITIONS THAT FAVOR DEVELOPMENT AND RAPID GROWTH OF HYPHOMYCETE FUNGI COLONIZING LEAF/NEEDLE LITTER?

The TAC literature does not provide much additional information concerning the environmental conditions that are conducive for fungal growth other than that presented in the answer to Question 2 above. This limited information is consistent with one other review paper (Murphy and Meehan 1991) in showing that nutrients in stream water and in liter (i.e., nitrate and phosphate) are important for microbes to build proteins as they digest carbon compounds from leaf litter. This would suggest that nutrient inputs, especially nitrogen from alder fixation, may favor fungal growth and boost litter conditioning in streams.

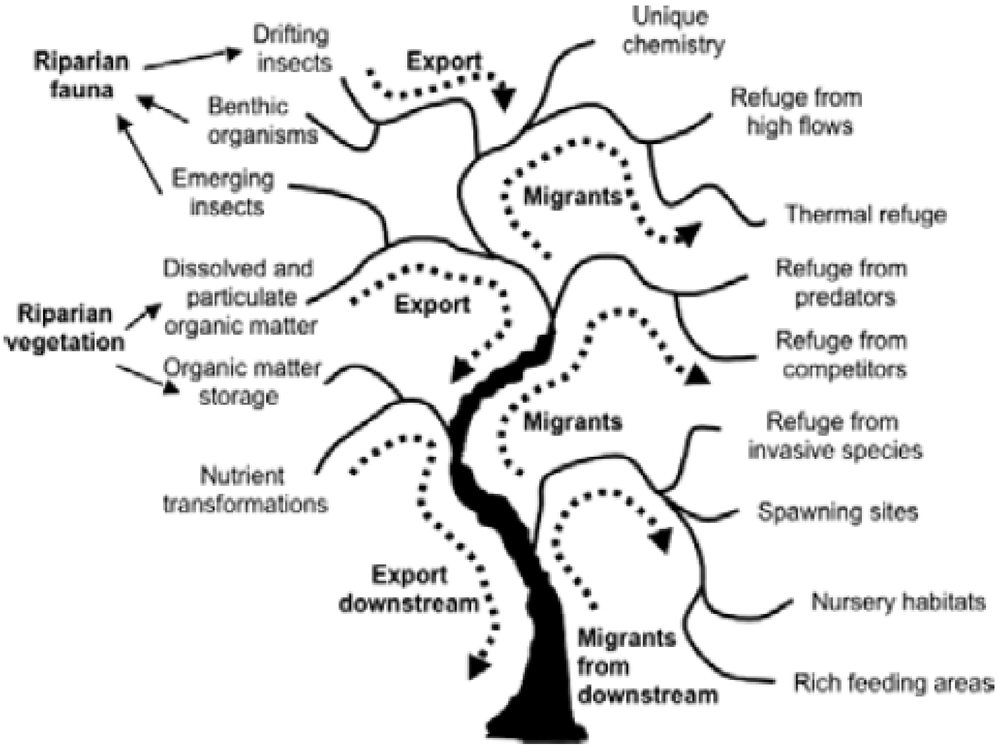
Figure 3. Importance of stream microbes and resident gut flora to shredders in providing assimilable materials including those refluxed forward from the hindgut to the midgut (Cummins 2002).



B. WHAT RIPARIAN VEGETATION STAND CHARACTERISTICS ARE MOST LIKELY TO PRODUCE THE BEST MIX OF FAST (RAPID PROCESSING RATES) AND SLOW (SLOW PROCESSING RATES) OF LITTER TRANSFERRED TO THE STREAMS?

The literature is consistent in showing that aquatic invertebrate assemblages are closely associated with litter composition (deciduous and conifer) and that alder is an important contributor of readily available and nutritious litter. Wipfli and Musslewhite (2004) found (in SE Alaska) that small fishless headwater streams dominated by red alder contributed more detritus and more aquatic invertebrates to downstream fish habitat than did tributaries not dominated by alder Invertebrate export was significantly correlated with the percentage of alder canopy cover. Similarly, Romero et al. (2005) showed that invertebrate drift under deciduous and mixed canopies was about 30% more abundant than under conifer in Oregon coastal streams.

Figure 4. Factors that contribute to the biological importance of headwater streams in river networks. Attributes on the right benefit species unique to headwaters and also make headwaters essential seasonal habitats for migrants from downstream. On the left are biological contributions of headwater ecosystems to riparian and downstream ecosystems.



Since we do not know what the optimum mix of fast and slow litter, it may be unrealistic to expect foresters to manage vegetation in the riparian zone specifically to create the optimum mix. However, an effective management goal for riparian vegetation may be to maintain a diverse mix of species that is spatially and temporally compatible with natural landscape features and timber management plans. For example, floodplains are naturally dominated by a deciduous plant community as a result of frequent disturbance (Rot et al. 2000). Targeted management in these settings may be one place where managing for red alder can support salmonids.

To apply such a strategy, alder patch size (length and width) and distribution could be based on the shape and spatial patterns of floodplain landforms within a drainage network. Similarly, alder patches may be targeted for tributary junctions (natural disturbance areas) of headwater stream segments that feed directly into fish bearing waters. Alder may be promoted in other riparian areas that have low site potential for conifer production, but would support alder because of its nitrogen-fixing ability.

Riparian alder patches may also be strategically located where their replacement of conifer does not have a significant influence on the recruitment of woody debris (e.g., along incised channels where the lack of bank erosion limits wood recruitment), but where biotic inputs are rapidly transported downstream to consumer communities. In California, three species of alder are important: red alder (*Alnus rubra*), white alder (*A. rhombifolia*) and mountain alder (*A. tenuifolia*). Red alder dominates near the coast, especially in the North Coast region. White alder is more common in riparian zones inland and at higher elevations. Mountain alder is found between about 8000 ft (south) and 3000 ft (north). Sitka alder (*A. sinuata*) occurs in Del Norte, Humboldt and Siskiyou counties. All of these species are nitrogen fixers, though the rates of fixation vary with tree biomass and environmental conditions.

4. What mix of riparian vegetation is most likely to produce the best populations of terrestrial invertebrates that are an important seasonal food source for juvenile salmonids?

In their study on the effect of red alder density on invertebrate and detritus subsides to downstream fish habitat, Wipfli and Musslewhite (2004) found that three-quarters of the macroinvertebrates were of aquatic origin, and one-quarter were terrestrial. The downstream flux of aquatic macroinvertebrates was directly related to alder density and basal area, but the flux of terrestrial macroinvertebrates was not.

Wipfli (1997) collected terrestrial macroinvertebrates and leaf fall in traps placed along streams in Southeast Alaska, including old-growth and young-growth stands, and sampled the stomach contents of salmonids. He found that terrestrial macroinvertebrates accounted for about half of the fishes' summer diet, and salmonids from young-growth sites ingested a higher proportion of terrestrial macroinvertebrates than fish from old-growth sites. The variability was too high and sample size too small to detect stand differences in terrestrial macroinvertebrates vs. aquatic macroinvertebrates input.

Allan et al. (2003) also found that terrestrial macroinvertebrates accounted for about half of the diet of coho salmon is Southeast Alaska. Their traps placed beneath red alder, and conifers (western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*)) captured higher biomass from the former than from the latter. Sampling of stems of six plant species found much higher biomass of terrestrial macroinvertebrates on deciduous (trees and shubs) than on coniferous trees. These findings are corroborated by studies in coastal Oregon where Romero et al. (2005) found that terrestrial inputs to invertebrate drift in streams with deciduous and mixed canopies was 30% more abundant than in streams with conifer canopies. They also showed that trout diet during summer-fall and prey availability were strongly related to shrub cover and somewhat less strongly linked with deciduous canopy.

The supply of terrestrial macroinvertebrates has been related to the degree of stand openness. In north-central British Columbia, Hoover et al. (2007) found that the drift density of aquatic insects was higher in uncut sections than in sections with 10 m buffers, but drift of terrestrial insects was directly related to stand openness. Terrestrial drift density was greater in clearcut reaches relative to buffered reach, and greater in buffered reaches than uncut reaches. Apparently early-stage successional vegetation produced more terrestrial macroinvertebrates that found its way to the stream when compared to late seral vegetation.

The differential timing of inputs of terrestrial and aquatic production demonstrates the relative importance of terrestrial inputs to salmonids, especially during summer. In Japan Nakano and Murakami (2001) found that salmonid diets were dominated by aquatic insects during winter-spring when terrestrial insect emergence was low and shifted to terrestrial insects during summer-fall, when the terrestrial emergence peaked and aquatic invertebrate biomass was nearly at its lowest. For several salmonid species, they found that the proportion of terrestrial prey in the diets during leafing seasons was much greater than that during defoliation periods. Similarly, Romero et al. (2005) found that terrestrial prey was most common in the diet of cutthroat trout during summer and fall when aquatic prey was relatively less abundant in Oregon coastal streams.

Although terrestrial derived food inputs are clearly important during summer, they can also be an important component for salmonids during winter. For example, in northern California White and Harvey (2007) found that earthworms flushed into streams during winter peak flow events contributed a major portion of the winter energy budget of cutthroat trout. It is not clear how riparian vegetation composition influences oligochaetes, but their occurrence during peak flows indicates an important linkage to the forest floor (e.g., floodplains) and suggests that riparian litter composition (e.g., deciduous litter from hardwoods) may play an important role. Winter flooding may also allow juvenile salmonids access to a wider range of food resources. For example, in Pudding Creek (western Mendocino County) Pert (1993) found that juvenile salmonids had fuller stomachs during winter high flow conditions than at other times.

The literature clearly shows that inputs of terrestrial insects are significantly enhanced by riparian deciduous trees and understory shrubs. Deciduous riparian stands and thinned conifer stands with understory shrubs both promote terrestrial insect fallout that subsidizes the summer-fall diet of juvenile salmonids. Terrestrial inputs of arthropods are less important during winter, but other terrestrial subsidies (e.g., earthworms) could play an important role for salmonids.

As stated above, the best mix of riparian vegetation is not explicitly addressed in the literature. The only conclusion, for now, is that more deciduous vegetation the better for terrestrial derived inputs. However, the trade-offs in terms of shade or reduced wood recruitment will need to be balanced against the gains of terrestrial subsidies. Perhaps the conifer-deciduous mix may be allocated in a longitudinal sequence of alternating patches of vegetation, rather than mixing conifer and deciduous at the same location. The riparian patch sequence may not have a specific dimension, but rather be determined by forest site potential and in disturbed areas, as suggested above. We discuss this in more detail in the Synthesis section (Chapter 7) of this report.

5. What riparian buffer width is required to achieve desired conditions of algal growth (question 1), litter turnover (question 2), and invertebrate prey for juvenile salmonids (questions 3 and 4)?

The studies that evaluated biotic productivity (i.e., periphyton, aquatic invertebrate, terrestrial invertebrate, and litter) responses to different buffer treatments offer some insight to the buffer width question. These studies show that algal biomass and invertebrate prey biomass generally increase with increasing canopy openness and/or increasing densities of deciduous vegetation (Wipfli & Musselwhite 2004, Danehy et al. 2007, Hoover et al. 2007; Table 1). Autotrophic production responds most with an open canopy and heterotrophic production responds most to a full canopy consisting of red alder. Biotic responses to moderate light levels or to deciduous vegetation ingrowth appears to be detectable in buffers that range from 10 m to about 20 m wide, especially in defoliated or thinned buffers (e.g., Danehy et al. 2007, Hoover et al. 2007) or in regenerated riparian stands (12 to 27 years old; Moldenke & Ver Linden 2007). Biotic productivity in streams with conifer-dominated buffer strips that are wider than about 30 m is similar to that observed in an unlogged forest (Newbold et al. 1980, Castelle and Johnson 2000, Moldenke & Ver Linden 2007).

In addition to the buffer width studies, our knowledge of the underlying mechanisms of how riparian conditions influence aquatic productivity can be used to guide buffer width decisions. As described in the Heat Section, light input to streams is controlled by the height and density of the riparian timber stand (primarily within 10 m of the stream; Sridhar et al. 2000) and is poorly associated with buffer width (Beschta et al. 1987). Also, the relative influence of buffers on light level varies with stream width; narrow streams can be heavily shaded and shade potential declines with increasing stream width. Therefore management of riparian stands to improve algal productivity might best be directed at stand density management immediately adjacent to small and moderate size streams. Increasing light input by stand thinning, is one approached that is suggested by the TAC literature (Danehy et al. 2007, Wipfli 2005 Wilzbach et al. 2005) to increasing aquatic productivity.

The literature clearly shows that aquatic macroinvertebrate production and terrestrial macroinvertebrate inputs are strongly influenced by the riparian vegetation complex and that deciduous vegetation, especially alder, is a high quality energy source (Primer, Allan et al. 2003, Richardson et al. 2004, Wipfli & Musselwhite 2004, Hoover et al. 2007). Although the riparian source distances for litter or terrestrial macroinvertebrates are not quantitatively addressed in the literature, it is reasonable to assume that stream adjacent trees and shrubs, especially overhanging vegetation, are probably the most important contributors of litter and terrestrial insect fallout.

Table 1. Summary of case study findings that evaluated flora and fauna responses to riparian buffer strips.

Reference & Location	Treatment	Response
Danehy et al. 2007 Coastal OR	Compared headwater streams with: clearcuts 2-8 years old, thinned 200 trees/ha and no harvest inner 15 m, uncut mature 2nd growth	Clearcut and thinned had higher diatom biomass than uncut sites, and clearcut had higher invertebrate biomass than thinned or uncut sites. Little difference in community assemblage between thinned and uncut
Wipfli & Musselwhite 2004 Southeast AK	Compared headwater streams with range of riparian red alder density (1–82% canopy cover or 0–53% basal area) within regenerated young-growth conifer stands (45-yr-old)	Aquatic and terrestrial invertebrate export (biomass and density) from headwaters is significantly correlated to percentage alder canopy cover
Hoover et al. 2007 North-central BC	Compared headwater streams with: uncut old-growth, 10 m foliated reserve strips, 10 m insect defoliated reserve strips, Clearcuts 4-8 years old	The degree of openness of the riparian reserve strip (clear cut > 10 m defoliated > 10 m foliated) was associated with increased and more variable terrestrial invertebrate drift, and decreased and more variable aquatic invertebrate drift
Moldenke & Ver Linden, 2007 Cascades OR	Compared headwater streams with: clearcuts 12-27 years old, 30-m buffers12-27 years old , no harvest	Canopy removal increased the biomass and density of total EPTs and all feeding guilds except scraper. No change in EPT yield between buffered and mature forest
Newbold et al. 1980 Northern CA	Compared: buffers < 30 m (range 3-25 m) buffers > 30 m (range 30-60 m), unlogged. Buffers in logged areas < 3 yrs old	Aquatic macroinvertebrate diversity was lower, and density was higher (mostly due to increases in Baetis, Nemoura, and Chironomidae) in narrow buffers compared to wide buffers or unlogged sites. Communities in streams with wide buffers not significantly different from unlogged.
Bottorff and Knight 1996 N. Fk. Caspar Creek, Mendocino Co.	Compared pre- and post-logging with 30-60m buffers, inner 15 m no harvest, out portion selective harvest. Post-harvest windthrow mortality ranged 4 to 30% Roads, skid trails and landings kept far from streams; steeper areas cable-yarded	Increased chlorophyll-a and algal biomass; doubling of alder leaf decay rate for 2 yrs; increased macroinvertebrate density and diversity, EPT density and diversity, and chironomid density.

Litter inputs to the stream are assumed to decline rapidly with distance from the stream bank. For example, FEMAT (1993) estimated that most litter input comes within 0.5 tree heights. Streambank erosion and flooding of the adjacent forest floor in flood plain areas is also assumed to be a significant source of litter and invertebrates. Therefore riparian management for high quality litter and terrestrial macroinvertebrate inputs would be most effective by maintaining stream adjacent (e.g., one tree crown width or about 10 m) deciduous overstory and understory vegetation, especially near streams with moderately confined or unconfined channels (i.e., locations susceptible to bank erosion and flooding). Management of riparian vegetation composition to promote aquatic productivity and enhanced fish production is suggested by researchers ranging from California to Southeast Alaska (Allan et al. 2003, Wipfli & Musselwhite 2004, Romero et al, 2005, Frazey & Wilzbach 2007).

Based on the foregoing, we infer that riparian management for a desired riparian condition that provides optimal algal growth, litter turnover, and invertebrate prey load to support juvenile salmonids would need to occur in a zone up to 30 m from the stream edge. Tree thinning to increase light or management for deciduous litter and terrestrial macroinvertebrates would be most effective on the inner-most portion (within 10 to 20 m) of the riparian stand.

6. What valley configuration (e.g. side slopes) and geomorphological characteristics (LWD, sediments, channel structures) set the boundaries for the buffer width required to achieve the objectives in question 5?

As we discuss in greater detail in Chapter 7, buffer width may not be the most effective variable for describing riparian functions. There is some evidence that buffer effectiveness may be better described by the structure, composition, characteristics and orientation of riparian buffers (Castelle & Johnson 2000; Young 2001).

Valley slope and confinement have been used as effective variables for delinating various regulatory domains (WA DNR 1997). These variables, when described within the context of network location and watershed disturbance regimes, strongly influence channel morphology and riparian landforms (Benda et al. 2004). Landforms (e.g., fans, floodplains, terraces) and associated disturbance regimes influence riparian stand composition and their spatial distribution in a riverine network (Naiman et al. 1998). For example, Rot et al. (2000) found that floodplains were dominated by deciduous species, especially red alder, but conifer dominated the overstory of other less disturbed landforms.

The shape and type of landform may be helpful in guiding buffer configurations including widths and other characteristics (e.g.

structure, orientation, density, etc). On landforms that are prone to flooding (e.g., floodplains, alluvial fans, tributary confluences) the width and shape of the flood prone zone delineates the riparian stand area that is functionally linked (i.e., through nutrient and organic cycling) to the aquatic ecosystem. The floodprone zone is the area prone to inundation by large floods, and it can be roughly approximated as twice the bankfull depth (Leopold 1994), although natural variation is substantial, and this metric may not be sufficiently accurate for regulatory purposes.

Debris flow, landslide and avalanche features which occur along steep and confined channels delineate another set of landforms that are often vegetated by invader deciduous stands (e.g., red alder, sitka alder, willow; Naiman et al. 1998). These landforms are linked to aquatic productivity by stochastic disturbances and in some cases (e.g,, hallows) through emergent seeps and springs that flow into adjacent streams. Also, the steep side slopes which are typical with these features may increase the probability that trees far from the channel will contribute litter and terrestrial invertebrates to the stream; a falling leaf will blow farther horizontally if the vertical distance above the creek is greater.

Topographic slope breaks adjacent to streams are known to influence local microclimate (Danehy et al. 2005 , Anderson et al. 2007) and may delineate another natural boundary that could influence nutrient and material transfers to streams. Information on the latter is lacking.

Small stream functions are still poorly understood (Moore and Richarson 2003). While there is a perception that small streams (generally 0 to 2nd order) are steep and confined, several studies suggest that many small streams are shallow and unconfined as well (Liquori 2002; Gomi et al. 2002). Thus the geomorphic variety associated with small headwater streams makes it difficult to describe broad generalities. While, organic matter is as important in small streams as in larger streams (Richardson et al. 2005), its not yet clear how or if the geomorphic expression of small streams is important with regard to nutrient issues.

7. Given a designated riparian buffer width necessary to achieve desired in-stream biological objectives (questions 5 and 6), what timber operations and management practices in riparian areas have been demonstrated to favor or inhibit these objectives? (i.e., How have selective harvesting and operations at differing distances from stream channel bankfull enhanced or inhibited the development of stream invertebrate communities that favor increased growth and density of juvenile salmonids?)

The literature on logging generally shows that removal of the forest canopy stimulates trophic pathways (see Primer and references in Table 1) that favor increased salmonid production in streams from California to Alaska (Murphy and Meehan 1991, Bisson and Bilby 1998). Similarly, increased tropic (food or nutrient) productivity has been observed in streams boarded by dense alder stands that regenerated following clearcut logging (Wipfli & Musselwhite 2004, Romero et al, 2005). However, this favorable response has been nullified for fish populations in streams where instream cover has been removed or habitat (e.g., pools) declined following reductions in LWD (Martin et al. 1986, Murphy et al. 1986, Bisson et al. 1987) or where increased summer temperatures reached lethal levels (Hall and Lantz 1969, Martin et al. 1986). These studies show that riparian management to promote fish-favorable trophic pathways, by itself, is not sufficient to maintain salmonid populations. Rather, riparian management needs to provide an adequate supply of LWD for fish habitat and associated ecological functions (organic processing, sediment storage, channel complexity; see Wood Section), and adequate shade for temperature control (see Heat Section).

The literature reviewed for Question 5 showed that stream invertebrate communities respond to riparian stand manipulations within about 30 m of the stream. Stand management beyond 30 m is not likely to have much influence on either light or litter inputs to streams, except in flood plains as described above.

8. Are there regional differences in the effects of natural disturbance or forest management activities on the biotic or nutrient riparian area functions? Do the same disturbance regimes or management activities have different effects in different regions (e.g. the coastal coast range, interior coast range, Cascade, or Klamath-Sierra Nevada)?

There are few if any studies that relate biotic/nutrient impacts of similar management activities to regional differences. But an understanding of the biotic/nutrient functions of the riparian zone suggests some possible interactions between regional characteristics and biological impacts. In the coastal zone, for example, daily fog can cause a downstream cooling trend as a stream flows toward the coast (Cafferata, 1990). Opening the riparian canopy along these streams may stimulate primary productivity (and invertebrate production) without risking a damaging increase in temperature. Further inland, especially at low elevations, stream temperature may be an important concern. In streams of the coast ranges, assuring an adequate supply of large woody debris (LWD) may be an important factor in determining buffer width, or marking trees to be retained in the riparian zone. In bedrock or boulder-controlled streams of the Sierra Nevada, LWD may be less of a concern.

The regional differences are addressed in more detail in the Synthesis section, since (as with the examples above) they involve the interaction of the biotic/nutrient function with some of the other functions.

INFERENCES FOR FOREST MANAGEMENT

The literature on logging generally shows that removal of the forest canopy stimulates trophic pathways (CBOF-TAC 2007; Table 1) that has led to increased salmonid abundances in streams from California to Alaska (Murphy and Meehan 1991, Bisson and Bilby 1998). Similarly, increased tropic productivity has been observed in streams boarded by dense alder stands that regenerated following clearcut logging (Wipfli & Musselwhite 2004, Romero et al, 2005). However, this favorable response has been nullified for fish populations in streams where instream cover has been removed or habitat (e.g., pools) declined following reductions in LWD (Martin et al. 1986, Murphy et al. 1986, Bisson et al. 1987) or where increased summer temperatures reached lethal levels (Hall and Lantz 1969, Martin et al. 1986). These studies show that riparian management to promote trophic pathways, by itself, is not sufficient to maintain salmonid populations. Rather, riparian management needs to provide an adequate supply of LWD for fish habitat and associated ecological functions (organic processing, sediment storage, channel complexity; see Wood Section), and adequate shade for temperature control (see Heat Section).

The reviewed literature suggests that riparian stand management for biotic and nutrient functions might consider longitudinal variations (e.g. upstream/downstream) along the stream rather than lateral buffer width. Such treatments could be designed to enhance invertebrate communities that favor increased growth and density of juvenile salmonids. For example, management of riparian stands in headwater stream segments that are adjacent to fish bearing waters could elevate headwater productivity and downstream material transport that would benefit the fish community (Wipfli 2005, Danehy et al. 2007). The buffer design could incorporate shade needs depending on temperature sensitivity (see Heat Section) of the fish bearing stream. Similarly, invertebrate and fish productivity could be boosted in fish bearing streams by managing riparian stands along stream segments. Considerations for temperature and LWD could be incorporated into management schemes depending on site specific conditions. For example, segments could be selectively thinned to promote instream nutrient and aquatic macroinvertebrate production and deciduous ingrowth. Some options might include:

- implement thinning treatments to open the canopy in segments with low temperature sensitivity to shade reduction,
- thinning on one side and in areas where LWD recruit potential is low,

- leave key trees with high potential for recruitment (e.g., leaning toward stream),
- alternate patches of deciduous and conifer that are large enough to promote trophic response (e.g., 100-200 m long), but short enough to maintain benefits of conifer zones, and/or
- intentionally place woody debris in managed segments to increase LWD loads and instream habitat on a stand rotation schedule (e.g., Cederholm et al. 1997).

Riparian enhancement activities could be strategically located in or near channel types (e.g., tributary junctions, flood plain segments) where aquatic productivity would benefit most (i.e., biological hotspots; Benda et al. 2004) from riparian resource subsidy. Such landforms create areas of concentrated productivity (e.g., frequent LWD, habitat complexity, detrital storage and processing, widened channel and increased light) and their riparian stands are often dominated by deciduous vegetation.

INFORMATION GAPS

- The zone of influence and utilization of invertebrates that are exported from headwaters to fish bearing streams (e.g., Wipfli, 2005) is unknown. Similarly, the headwaters source area that needs to be managed for biotic and nutrient exports is not well defined.

- The biologically effective length of riparian vegetation patches that are large enough to stimulate trophic energy pathways yet small enough to maintain shade control or wood debris recruitment in adjacent patches needs to be defined. Similarly, options for management that are logistically feasible should be investigated.

- The potential to stimulate trophic pathways through riparian management will vary regionally. More information will be needed for areas (e.g., Sierra and Central Valley) that have limited research.

GLOSSARY

autotrophic	Literally, self-feeding. Refers to organisms that obtain energy from sunlight or inorganic compounds or elements, such as nitrate, sulfide or reduced iron
Chironomid	A small non-biting fly, the larvae of which are sometimes an important food resource for fish
Diatom	any of numerous microscopic, unicellular, marine or freshwater algae of the phylum Chrysophyta, having cell walls containing silica.
functional feeding groups	Groupings of aquatic macroinvertebrates according to their mode of feeding. Includes shredders, scrapers, collectors, filter feeders and predators.
heterotrophic	Literally, other-feeding. Refers to organisms that obtain energy from reduced carbon (dead or living plant or animal tissue)
hydrophobic	Water repellant. Hydrophobicity in soils is sometimes caused by condensation of hydrocarbons (waxes and oils) during a fire.
hyphomycetes	A division of fungi, with naked spores borne on free or only fasciculate threads
hyporheos	Literally, underflow. Refers to water flowing in the bed or banks of a stream and exchanging frequently with surface flow
Oligochaetes	Any of various annelid worms of the class Oligochaeta, including the earthworms and a few small freshwater forms
periphyton	Literally, surface plants. Generally refers to algae growing on the surface of rocks or debris in a lake or stream
phenology	The study of timing of biological events in nature, such as flowering, insect emergence, etc.

trophic pathways	The pathways that energy follows in a food chain, from primary producers, to consumers, to top carnivores.

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