Sound Watershed Consulting
Creating Functional Water Environments

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

Chapter 5
WOOD EXCHANGE FUNCTIONS

for

The California State Board of Forestry and Fire Protection

September 2008

2201 Melvin Road, Oakland, CA 94602
(510) 927-2099
www.soundwatershed.com

Hydrology
Geomorphology
River Ecology
Restoration Design
Sustainable Forestry
Integrated Watershed Management

5) WOOD 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

Prepared by

Mike Liquori

Dr. Lee Benda

Dr. David Ganz

with

Dr. Doug Martin

Dr. Robert Coats

September 2008

SWC Ref# 1013

Table of Contents

EXECUTIVE SUMMARY

Forested environments strongly influence salmonid habitat in California through the processes of woody debris entering the stream from riparian areas. This report describes the mechanisms for wood recruitment to the stream environment, the influence of forest management, and factors that affect riparian buffer design.

There are three dominant sources of instream wood; bank erosion, streamside landslides, and treefall from within riparian areas. Each of these sources is influenced by the dominant type, frequency and magnitude of disturbance processes (fire, flood, landsliding, infestation, etc), as well as the rates of competition mortality associated with the existing stand structure. Disturbance, mortality and tree growth in riparian stands are dynamically linked.

In California second-growth forests, approximately 40-60% of observed instream wood comes from bank erosion, approximately 30% comes from streamside landslides, and the remaining amount comes from treefall. These rates vary substantially based on the geographic (e.g. region) and geomorphic (e.g. landscape condition) context for the site.

Once in the stream, wood is subject to transport down the channel network either during floods (fluvial) or debris-flows. Wood that is carried by debris flow only occurs in certain terrains (typically steep, confined headwaters). Wood that is carried by floods is typically shorter than the channel width.

It can be important to understand the existing stand conditions and successional trajectory of the riparian stand because the riparian stand structure strongly influences the qualities of recruited wood and the rate of recruitment. The existing stand structure and successional trajectory also influences the types and qualities of disturbances that can occur at any given site, and disturbances are one of the primary recruitment processes for instream wood.

Forest management can manipulate riparian stand structure in ways that a) affect the growth and mortality dynamics for the stand and b) influence the types, qualities and risks of disturbances. Forest management can also reduce tree recruitment potential and shift the functional inputs from various exchange functions. Management has the potential to improve existing conditions that reflect legacy forest practices. Management can also alter short-term and long-term supply and characteristics of wood. Therefore, management within riparian

zones must be conducted carefully, and with clear functional objectives.

Riparian silvicultural objectives that would support ecological functions important to salmonids (and other fauna) should balance competition mortality objectives, growth objectives, and disturbance risks in ways that support exchange function objectives based on a diagnosis of site requirements. Diagnoses may be generalized by the spatial context of the site by considering regional variations as well as watershed-scale variations in the dominant processes that affect stand evolution (i.e. disturbance types). Diagnoses should also consider the expected stand growth and mortality processes based on conditions that influence stand dynamics (e.g. tree species, cohorts, density, size, etc). Together, the major factors that are reported to influence wood recruitment conditions include:

- Existing Stand Density, Composition And Structure
- Stream Type, Order and Watershed Context
- Vegetation Type and Soil/ Site Index
- Regional Context
- Disturbance Context

Riparian management strategies require consideration of both science and policy. The reviewed literature offers many opinions, but little hard data to evaluate the scientific effectiveness of any approach. Ultimately, the choice of the best approach must be guided by forest policy. The ranges of policy alternatives includes:

Riparian Reserves: This approach seeks to maintain large buffer widths to minimize management effects within riparian areas, specifically those indirect management effects on natural rates of disturbance. This approach typically calls for uniform and continuous riparian buffers of up to two site-potential tree heights on fish-bearing streams and one site-potential tree height on non-fish streams. The underlying basis for this strategy is that over long periods of time (typically centuries), late-seral conditions will become re-established in riparian areas, and that such conditions best represent the long-term conditions suitable for salmonids.

Selective Management: This approach seeks to actively design the characteristics of riparian forests (e.g. size, height, species) in a way that influences future wood recruitment potential (e.g. timing of mortality, exposure to disturbance risks) and other functions. Its focus is often to maximize the benefit to riparian functions while preserving the capacity to operate on forest lands to achieve other resource objectives. It achieves this focus by encouraging a stand composition that targets wood recruitment characteristics most suitable to the specific stream environment. This approach recognizes that the total wood volume grown onsite is strongly influenced by stand structure (density, species, age-distributions, etc), and that tree volume and diameter can be manipulated to meet management objectives.

Proactive Enhancement: Another approach described by the reviewed literature is the concept of proactive instream restoration and enhancement in the form of wood placement. The ability to properly design and implement restoration or enhancement projects requires knowledge of hydrology, hydraulics, geomorphology, biology and engineering practices. Instream wood placement is a practice that is continuing to evolve in many land-use settings, and the general perception is that such projects are overall a benefit to salmonids.

There are a wide array of tools and methods available that can objectively inform these management strategies using scientific approaches. There are also several existing information gaps that could improve riparian management.

RECOGNIZED EXCHANGE FUNCTION ROLES & PROCESSES

Forested environments strongly influence salmonid habitat in California through the processes of woody debris entering the stream from riparian areas. The relative importance of riparian forests in regulating wood delivery to the stream environment is governed by multiple interacting factors (biotic and abiotic) that have been described by CBOF-TAC (2007), and which form the foundation of our review. These principles include:

- In-channel wood plays an important role in determining aquatic habitat conditions and riparian ecology by affecting flow hydraulics, regulating sediment transport and storage, influencing channel morphology, and promoting diversity of channel habitat
- Wood is recruited to streams through tree fall, bank erosion, debris flows, and landslides. These processes are strongly influenced by mortality through competition, infestation or disease, as well as disturbance processes like fire, flooding, wind, etc
- In steep channels, wood accumulations often help to trap sediment and promote a stepped morphology.
- Logging activities adjacent to streams that eliminate or severely reduce wood storage in streams can have negative impacts for salmonids
- Wood transport through the channel network is an important source of woody debris for streams that are typically inhabited by salmonids, and transport occurs via both fluvial and debris flow processes
- The legacy of historic forest and stream management practices continues to have significant impacts on the stream environment, and full recovery of natural recruitment characteristics might be over a century or more away
- Forest management practices in riparian zones can have lasting influences (both positive and negative) on the recruitment of woody debris over time

- The dynamics between forest stand growth, wood recruitment and channel response are complex and vary widely across both time and space

- Wood loading and instream wood characteristics vary widely over the landscape, and a clear scientific consensus for how much wood is sufficient to support salmonids needs has been elusive

- The size of functional instream wood generally increases with increasing basin size, although some have argued that large wood in headwater streams might have important functional roles as well

RESPONSES TO KEY QUESTIONS

The Key Questions are grouped into the following sections:

1.2.1 **Mechanisms for Wood Recruitment** – this section includes questions that relate to the processes and functions within riparian areas that support wood recruitment.

1.2.2 **Management Influences on Wood Recruitment** – this section discusses the manner in which management and/or disturbances can affect the natural mechanisms for recruitment

1.2.3 **Factors Affecting Buffer Design** – this section describes those factors that should be considered in developing buffer strategies.

1) Mechanisms for Wood Recruitment

In this section, we describe the key natural wood recruitment processes that occur in forested landscapes of California. Later in this chapter, we address differences in the way that recruitment processes occur in managed forests.

The literature on wood recruitment to streams over the last 30 years has identified the major recruitment mechanisms for wood that is applicable in a general sense to channels of all sizes and in most geographic areas (Keller et al 1995). While most of the wood recruitment studies in California and elsewhere have focused on larger fish-bearing channels, the processes of wood recruitment are generally similar across small headwater (low-order) and larger fish-bearing streams, although there are some specific differences that we describe below. Natural recruitment processes include:

1. Bank erosion and channel migration processes that recruit trees by undercutting the channel margins (Keller et al. 1996; Martin and Benda 2001; Benda et al. 2002; Marcus et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005).

2. Mass wasting processes, including landslides, earthflows, debris avalanches, debris flows, etc (Benda et al 2002; May and Gressweld 2003; Reeves et al. 2003).

3. Treefall generated from toppling of trees in the riparian zone (McDade et al. 1990; Robison and Beschta 1990; Martin and Benda 2001; Benda et al. 2002; Liquori 2006).

Trees can die in response to competition mortality, disease, infestation or disturbances that kill trees and delivers woody debris before mortality would typically occur from competition (Bragg and Kershner 2000; Liquori 2006).

Disturbance typically plays a very important role in wood recruitment in California forests, as it typically sets the context for natural recruitment processes and the evolution of the forest stand. Natural disturbance processes significantly influence the rates of recruitment. Fire, flood, wind, landslide and similar natural disturbances are the primary source of wood recruitment in most unmanaged landscapes. The effect of these disturbances is highly dynamic – disturbances affect the condition of the riparian forest, and the riparian forest condition can affect the probability of disturbance (Benda and Sias 2002; Reeves et al. 2003; Bisson, Rieman et al. 2003; Nakamura and Swanson 2003). For example, wildfire in the riparian zone results in mortality that can recruit wood through treefall, adding a rapid influx of wood to streams that can increase channel migration processes, increasing bank erosion and thus increasing additional wood loading (Benda and Sias 2003).

Bank Erosion

Bank erosion delivers trees and downed wood to the stream by undercutting the banks, typically during large floods. Bank erosion tends to be episodic, and is related to the rate of channel migration or widening. Thus the proportion of instream wood delivered from bank erosion will vary over space and time.

Most trees immediately adjacent to streams will be recruited (McDade et al. 1990; Liquori 2006). In many mature 2nd-growth streams, bank erosion delivers about 40 – 60% of the observed wood loading (Figure 1), similar to the loading rate in old-growth sites (Figure 2), which provided about 30-55% of the observed instream wood (Benda et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005).

Larger, low-gradient channels are more prone to bank erosion through channel widening, meandering, and/or migration, and thus tend to recruit proportionally more wood than steeper, confined channels. However, landslide recruitment of trees adjacent to smaller channels can reverse this trend. Trees recruited through bank erosion typically are rooted within about 1 m of the channel at the time of recruitment

(McDade et al 1990) and recruitment of key pieces[1] is also typically dominated by bank erosion (Benda et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005).

It need not require an extensive amount of erosion to supply trees from bank erosion. Wood budget calculations indicate that as little as 1.5 feet per decade of average bank erosion can supply wood at loads similar to those observed in California. At this rate, it would take 700 years to erode through a standing 100 foot buffer. Of course, actual bank erosion processes are episodic and disperse, and occur in association with large floods, channel migration periods, excessive instream sedimentation or wood accumulation (e.g. from landslides, etc).

Mass Wasting (landslides & debris flows)

Streamside landslides can be significant contributors of large woody debris in steep landscapes prone to hillslope failure.

In the Northern California Redwood region, streamside landsliding was important at selected sites with steep inner gorges, primarily in the old growth forest of Little Lost Man Creek (Benda et al 2002). In old growth sites (Prairie and Little Lost Man Creek) streamside landsliding accounted for 50% of the observed woody debris. In second growth forests, streamside landsliding accounted for 30% of observed woody debris.

May and Gresswell (2003) documented that along headwater first- and second-order streams in the central Oregon Coast Range, streamside landsliding along inner gorges was a dominant recruitment process and thus wood source distances were longer than predicted by mortality alone in those areas. In larger alluvial channels, slope instability was less important but wood transfer from fluvial transport becomes important (Braudrick and Grant 2000).

Treefall

Treefall supplies wood to the stream from the riparian forests, and typically includes trees that die from competition mortality, wind

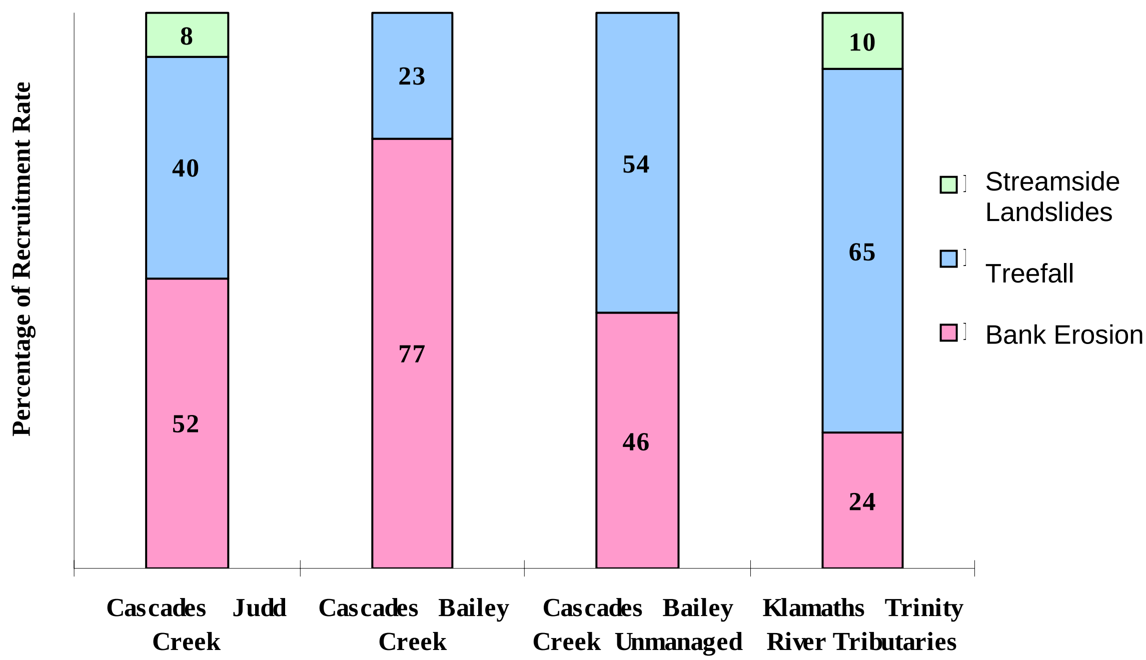
---

[1] *Key pieces are large diameter trees that are structurally important in supporting woody debris jams in alluvial rivers*

damage, insect damage, root disease, infestation, animal damage, and other processes. Wood budget studies typically cannot differentiate between competition mortality and other forms of treefall (e.g. windthrow, ice or snow weighting, animal damage, etc).

Treefall from riparian stands will typically fall in a random orientation (Robison and Beschta 1990; McDade et al. 1990), with the exception of those processes that have mechanical influence (e.g. wind or ice damage). As the tree dies, roots decay and the loss of root support will cause the tree to topple. Treefall that occurs in response to some disturbances can significantly increased percentage of treefall directed toward the channel (McDade et al. 1990; Liquori 2006).

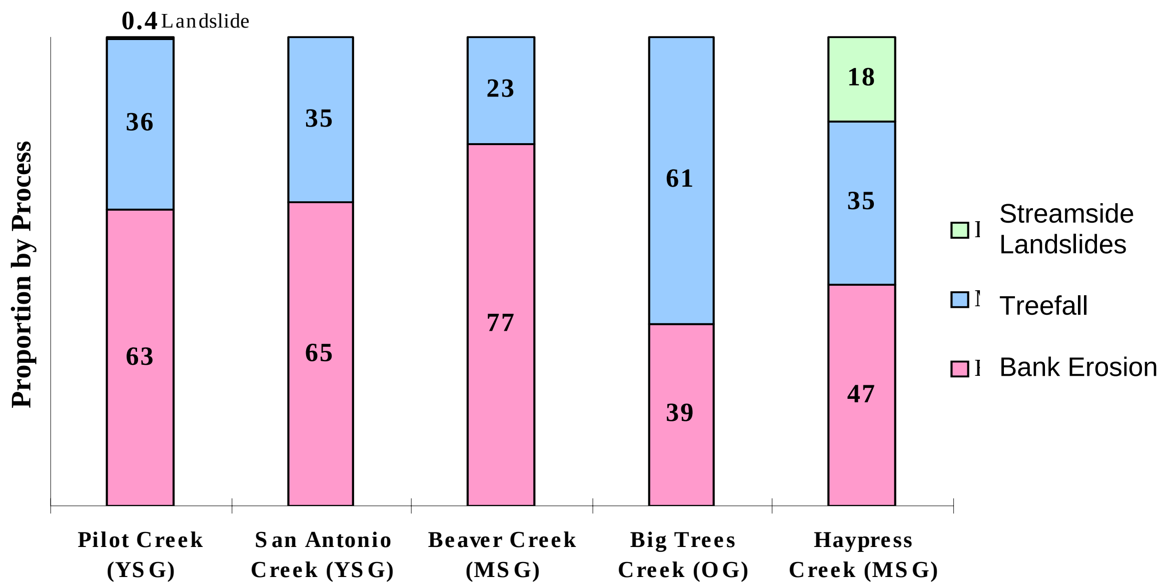
Figure 1. Percentage of wood recruitment by different processes in streams located in the Southern Cascades and Klamath Mountains of Northern California (Benda et al. 2003).



Treefall recruitment is typically limited by the tree height, and the probability of recruitment upon falling declines non-linearly with distance (Robison and Beschta 1990). Trees immediately adjacent to the stream only have a 50% probability of recruiting to the stream, unless influenced by wind (Liquori 2006). Trees that are farther than a tree-height generally cannot recruit to the stream, unless a) the valley is steep enough to allow the tree to slide downslope along small streams or b) on large rivers, floods can redistribute wood both away from and toward the channel.

In the Northern California Redwood region, treefall accounted for 20-45% of wood recruited in old-growth sites and 40% in second-growth sites (Benda et al 2002) (see Figures 1 and 2). In northern California's coastal redwood region, average forest morality rates are higher in second growth forests (0.9%/year) compared to much lower average mortality rates in old growth redwood forests (0.04%/year). This resulted in a higher wood loading in second growth forests from mortality recruitment (4 m^3/km/yr in second growth vs. 2.5 m^3/km/yr in old growth), although the wood supplied was of smaller diameter (Benda et al. 2002).

Figure 2. Percentage of wood recruitment by different processes in streams located in the Sierra Mountains (western slope) in Northern California (Benda et al. 2005). YSG=Young Second Growth; MSG=Mature Second Growth; OG= Old-Growth. Note mortality in this study refers to treefall recruitment.



<u>HOW DOES WOOD RECRUITMENT DIFFER BETWEEN LOW-ORDER AND HIGH-ORDER STREAMS?</u>

Fundamentally, wood recruitment processes in lower-order channels are similar to higher-order streams, in that the same processes of bank erosion (e.g., landsliding and treefall) are relevant, although the relative proportion of wood recruited from each mechanism varies. Recruitment processes and source distances are highly variable and depend on local topography and channel conditions.

The proportion of wood that comes from the 3 primary mechanisms (treefall, bank erosion and landsliding) shifts somewhat between headwater streams and high-order streams. Bank erosion recruitment is proportionally more important in high-order streams (typically responsible for 40 – 60% of observed wood). Similarly, landsliding is often more important in low-order streams, particularly in steep, confined landscapes (Table A).

Table A[2]. Summary of wood recruitment information in high-order (fish- bearing) streams.

Location	Forest Type	Treefall[3]	Bank Erosion	Streamside landsliding	Fire	Debris Flow[4]	Slash[5]	Citations
Redwood N. Coast CA	Second growth	45%	36%	19%	n/a	Observed not quantified	Signif.	Benda et al. 2002
Redwood N Coast CA	Mature	38%	50%	12%	n/a	n/a	Signif.	Benda et al. 2002
So. Cascades N. CA	Second growth	46%	52%	2%	n/a	n/a	n/a	Benda et al 2003)
Klamath Mtns. N. CA	Second growth/ Mature	39%	43%	17%	n/a	Observed not quantified	n/a	Benda et al 2003)
Central CA Coast	Second growth	26%	59%	16%	n/a	Observed not quantified	Signif.	Benda et al 2003)
Sierras Eastern Central valley	Second growth	37%	53%	10%	n/a	n/a	Locally Signif.	Benda et al. 2005
Sierras Eastern Central valley	Mature	61%	---	---	n/a	n/a	n/a	Benda et al. 2005
Oregon Coast Range	Mature	n/a	n/a	n/a	n/a	46%	n/a	Reeves et al. 2003
Oregon Coast Range	Mature	Dominant	?	Less important	n/a	?	n/a	May and Gresswell 2003

---

[2] *Because some of the field sites in headwater streams are contained within studies that evaluated mostly larger channels (see above and for example Benda et al. 2002), this section on larger streams includes in the cited statistics data in headwater streams. This is because the cited studies did not differentiate between headwater and larger streams and the exclusion of headwater data would not significantly affect the results reported below.*

[3] *Includes the processes of suppression mortality, disease, insects, and blowdown*

[4] *Refers to debris flows in headwater, first- and second-order streams that deliver WOOD to larger fish-bearing channels at the confluence with low-order tributaries.*

[5] *Refers to old logging debris left in channels prior to modern forest practice rule.*

In addition to the primary recruitment mechanisms, wood loading in low-order streams is also affected by:

- Landslides from steep hillslopes (May and Gresswell 2003;)
- Valley confinement that can prevent falling trees from intersecting the channel, and can increase the rates of breakage

Field studies of wood recruitment processes to headwater channels (specifically first- and second-order channels) that identified specific wood recruitment processes, are limited to Benda et al. (2002) in the Redwood region of northern California, May and Gresswell (2003) in the central Oregon Coast Range, Jackson et al. (2001) in the Olympic Peninsula, western Washington, and Benda et al. (2003) in the southern Cascades of northern California. In the context of these limited data sets, mortality, bank erosion and streamside landsliding are all important wood recruitment processes (Table **B**). Although streamside landsliding can dominate in certain settings, bank erosion and mortality can be dominant sources of wood.

Table B) sources of observed wood recruitment from headwater channels.

Location	Forest Type	Treefall[6]	Bank Erosion	Streamside landsliding	Fire	Slash[7]	Citations
Redwood North Coast CA	Second	22%	39%	39%	n/a	Signif.	Benda et at. 2002
South Cascades CA	Second	78%	22%	n/a	n/a	n/a	Benda et al. 2003
Oregon Coast Range	Mature	?	?	Dominant	n/a	n/a	May and Gresswell 2003

Another study pertaining to headwater channels was that of Bragg et al. (2000) in the central Rocky Mountain region, which concentrated on modeling wood recruitment from stand mortality only, using a forest vegetation simulator (Wykoff et al. 1982) that predicts forest growth and mortality.

Marcus et al. (2002) evaluated wood storage and movement across a range of stream sizes (14 – 242 km^2) and determined that wood storage is highest in the smallest channels, and has increased due to recent floods (assumed increased bank erosion recruitment). Intermediate size channels are approximately in equilibrium in terms of wood storage as input can equal output due to effective fluvial transport.

---

[6] *Includes the processes of suppression mortality, disease, insects, and blowdown*
[7] *Refers to old logging debris left in channels prior to modern forest practice rule.*

Less wood can be found in larger rivers due to high wood transport and storage overbank.

In addition to the primary recruitment mechanisms described above, wood loading in higher-order streams is also affected by:

- Import and export of woody debris from fluvial transport (Keller et al. 1996; Benda and Sias 2002; Hyatt and Naiman 2001; others).
- Debris flows that transport wood stored in headwater streams and deposit logs and sediment at confluences with larger fish-bearing channels (Benda et al. 2002; Reeves et al. 2003).

TO WHAT EXTENT DO LOW-ORDER STREAMS DELIVER IN-STREAM WOOD TO HIGHER ORDER, FISH-BEARING STREAMS?

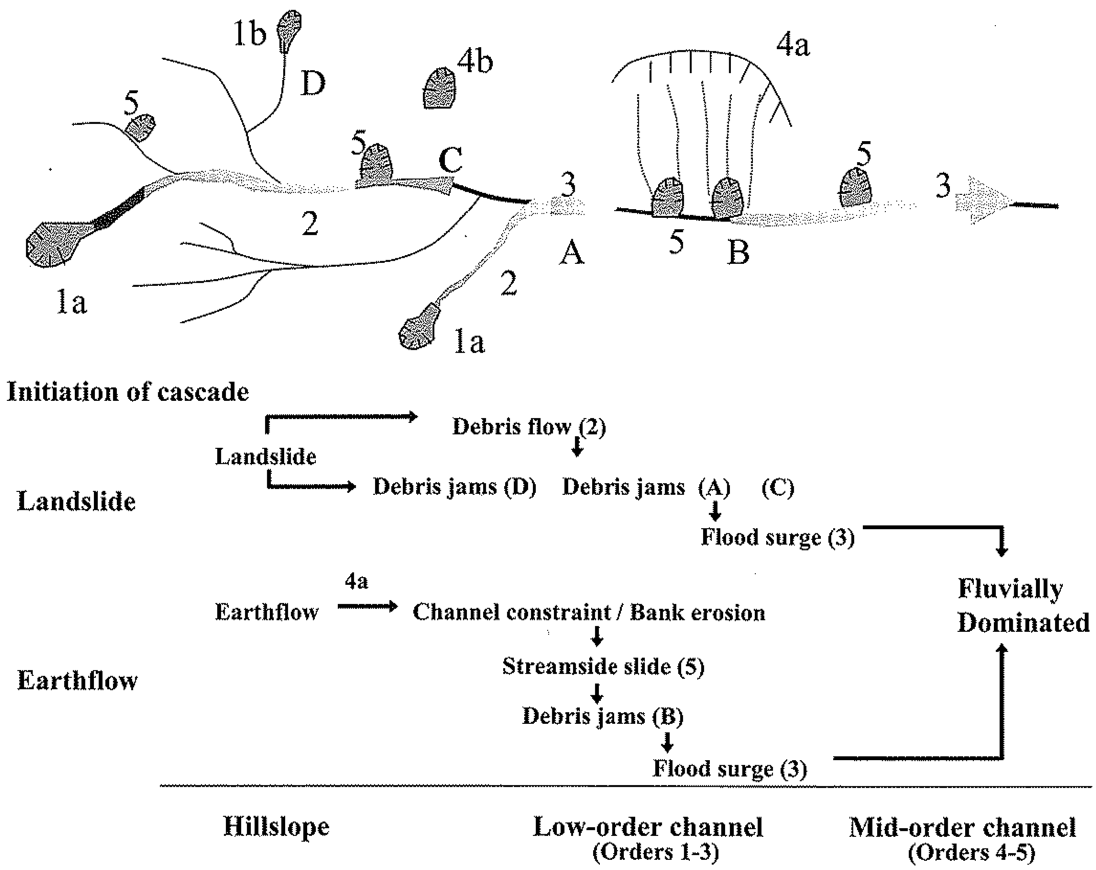
There are two primary mechanisms for delivering woody debris from low-order streams to higher-order streams: fluvial transport and debris flow transport.

Debris-flows

In some landscapes, including parts of coastal California, wood derived from debris flow deposits can play an important ecological role (Reeves et al. 2003; May and Gresswell 2003; Bigelow et al. 2007) although few specific studies have documented interactions between debris-flows and streams in California. Low-order headwater streams can be prone to debris flows in certain physiographic areas in California and can be a source of wood to higher-order fish-bearing streams (Coast Ranges and Klamath Mountains primarily). Wood from debris flows is recruited to the steam via landslides and earthflows that are initiated on hillslopes, and routed to the channel environment (Figure 3).

It was difficult to allocate woody debris from debris-flow sources in the California wood budget studies (Benda et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005) because of the uncertainties of aging debris flow deposits in this terrain. Only one study in the Klamath Mountains documented the importance of debris flows as sources of key pieces, and it identified only 11% of the total wood recruited came from these sources (Benda et al. 2003). In the central Oregon Coast Range, Reeves et al. (2003) concluded that upslope sources of woody debris to fish-bearing streams from unmanaged landscapes can be important in steep, confined landscapes, accounting for 65% of the pieces and 46% of the volume.

Figure 3) schematic of disturbance cascades in headwater environments. Earthflows and landslides deliver hillslope wood to the channel network, where it can be routed downstream by debris flow processes and flood surges. Susceptibility to debris flows can be identified by geomorphic criteria associated with the channel and hillslope environment (*from Nakamura and Swanson 2003*).



Fluvial Transport

Fluvial transport from low-order channels is another potential source of wood to higher-order streams (Keller et al. 1995). The extent of fluvial transport depends on the size of available instream wood and the power to transport that wood, which increases with contributing basin area. When wood is sufficiently large in headwater streams (i.e., piece length > channel width), transport rates tend to be very low (Benda et al. 2002; Benda et al 2003; Benda et al 2004; Benda et al 2005).

In one study in the California Coast Range (Benda et al. 2004), the distance upstream of low- to high-order channel confluences where fluvial wood transport is predicted to supply wood to larger fish-bearing channels ranged from 325 – 650 ft (100 – 200 m).

Similarly, wood transport was predicted using a simple wood transport model (Benda and Sias 2003) and using data on jam size and frequency. The predicted wood transport from low-order, headwater channels to larger fish-bearing streams extended upstream of the junctions 325 – 650 ft (100 – 200 m), with wood piece sizes ranging from 3 – 9 ft (1 – 3 m).

Fluvial transport of wood can lead to accumulations in woody debris jams when trapped by large, stable "key" pieces of wood (Keller et al 1995). Thus downstream reaches can experience higher wood loadings than upstream reaches where riparian conditions are similar. Once a river exceeds the width of the tallest recruited trees, this relationship reverses as wood is exported out to sea (Martin and Benda 2001).

TO WHAT EXTENT AND IN WHAT WAYS DOES PLANT SUCCESSION STAGE OR VEGETATIVE COMMUNITY HAVE AN EFFECT [*ON WOOD RECRUITMENT*]?

Understanding the existing stand conditions and likely successional trends can be helpful toward guiding riparian conditions toward desired states. Successional trajectories can be predicted using relative stand density indices or wood recruitment models (e.g., Bragg et al. 2000; Welty et al 2002).

Successional status affects the potential for wood recruitment in multifaceted ways (Bragg et al 2000; Rot et al 2000). Liquori (2000) described successional implications for riparian management by recognizing that the stage of succession influences the dominant riparian exchange functions. For example, competition mortality is higher during stem exclusion phases (Rot et al 2000), however the quality of woody debris can be limited, depending on factors like stem density and species. During successional periods of vigorous stand growth, competition mortality can decline significantly, causing periods of lower treefall recruitment that can extend for several decades.

Forest successional trajectories can be altered either directly (via management treatments) or indirectly in response to altering disturbance regimes. For example, clearcuts in windprone landscapes can increase the risk of windthrow in ways that transition a stem exclusion stand toward an understory reinitiation stand (Liquori 2006). Similarly, dense riparian buffers in fire-prone landscapes can lead to increased frequency of crown fires, which can rapidly transition a mature stand toward a period of very high treefall recruitment followed by an extended period of minimal treefall recruitment as the stand stage transitions toward stand initiation (Agee 1993).

In unmanaged forests, the lack of disturbance can affect the forest floor, soil temperatures, and some types of microbial activity. Size distributions of trees in unmanaged coniferous forests are strongly related to disturbance history and time since previous disturbances (Oliver and Larson 1996). Typical patterns of size distribution can be identified, although many stands will deviate from idealized patterns. In centuries-old, late successional forests, frequency distributions of trees typically approximate a negative exponential distribution. Intermediate disturbances such as partial fires can remove understory and overstory trees, altering horizontal and spatial pattern of canopy foliage. In some cases, different disturbance histories can produce similar size distributions of trees.

Species assemblages can also influence successional dynamics. For example, in coastal California, mixed Douglas fir (*Psuedotsuga menziesii*) and redwood (*Sequoia sempervirens*) stands have different rates of mortality and different recruitment mechanisms. Douglas fir grows faster during early stand establishment periods, but is more prone to competition and windthrow (Surfleet and Ziemer 1996). Later stand development is dominated by redwood growth and Douglas fir mortality. Young redwood mortality is often low, because of several physiological adaptations in redwood that promote survival under limited growing conditions. Old-growth coast redwood eventually die due to wind throw, toppling, very large floods, and heart rot (Stone and Vasey 1968). So in the absence of disturbance, recruitment rates in pure redwood stands are lower than a mixed species stand where competition mortality can occur.

Overall, recruitment from competition mortality processes can be one of the slowest ways to recruit wood to streams. Mortality rates in forest stands usually range from 0.02% to as much as ~1% per year, and only a fraction of these dead trees are recruited to streams. In general, second growth forests have higher competition mortality rates and higher growth rates when compared to older (old-growth or mature) forests due to increased stem differentiation in response to pressures from limited growing space. In one study, second growth forests had an average treefall recruitment (presumably from competition mortality) rate of 0.9%/yr compared to 0.04%/yr in old growth, a 20-fold difference (Benda et al. 2002). However, competition mortality tends to kill the smallest, weakest trees in the forest, and these trees generally provide lower quality wood to the stream than wood provided through disturbances. Reliance on competition mortality can extend the period of recovery in the absence of other disturbance mechanisms for recruiting wood.

Forest successional pathways establish the context for disturbance risks in many landscapes. For example, fire asserts a significant influence on wood growth and recruitment (Reeves et al. 2003). Models of stand replacing fires with recurrence intervals of 150 and 500 years (representing a gradient from humid temperate to more arid forests) can contribute 50% to 15% of the long term wood to streams from post fire toppling (Benda and Sias 2002). Underburns can promote growth in older cohorts by reducing competition from intermediate and suppressed trees.

In general, variation in forest types (and associated biomass density) in California strongly influences the amount of wood that is found in channels. Based on wood budget studies in northern California, the largest wood storage occurs in the coastal redwood zone and the least occurs in the Southern Cascades and Sierras (Figures 4A-C).

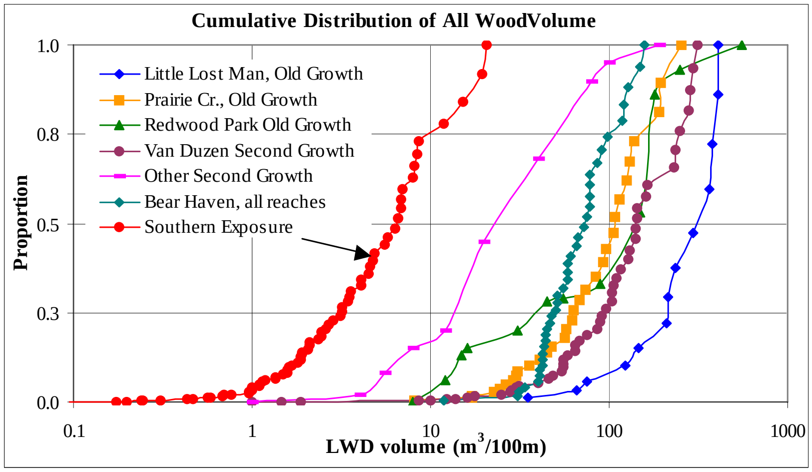
WHAT IS THE EFFECT OF STAND-LEVEL RIPARIAN FOREST CONDITIONS ON WOOD DELIVERY TO STREAMS TO MAINTAIN SALMONID HABITAT?

There is limited information about the effect of stand conditions on wood recruitment, however, the amount of wood loading under natural conditions is generally related to the qualities and quantities of trees available in adjacent riparian stands (Keller et al 1995). Rot et al. (2000) found that stand age and stand basal area did not influence the in-stream number of wood pieces, wood volume, pool spacing, percent pools, or percent of wood-formed pools. However, stand age did correspond to the diameter of instream wood.

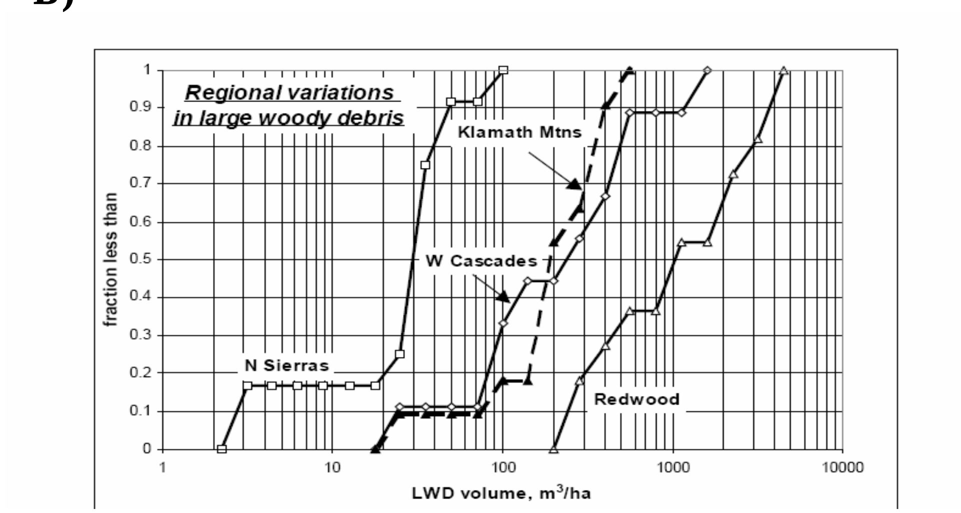
Wood is important for salmonids as it is responsible for forming pools in alluvial environments, helps to sort sediment for spawning, and provides cover (Cederholm et al 1997; Reeves et al 1995; Bisson, Rieman et al. 2003). Many field studies have linked fish habitat (e.g., pools, cover, gravel) with wood across the PNW over the past 20 to 30 years, a conclusion outlined in the wood Primer (CBOF-TAC 2007).

Figure 4. Variation in cumulative wood storage is shown across several northern California's physiographic regions (A) From Benda et al. 2002; Benda et al. 2003; Benda et al 2004; Benda et al. 2005) and Lisle 1999 (B&C).

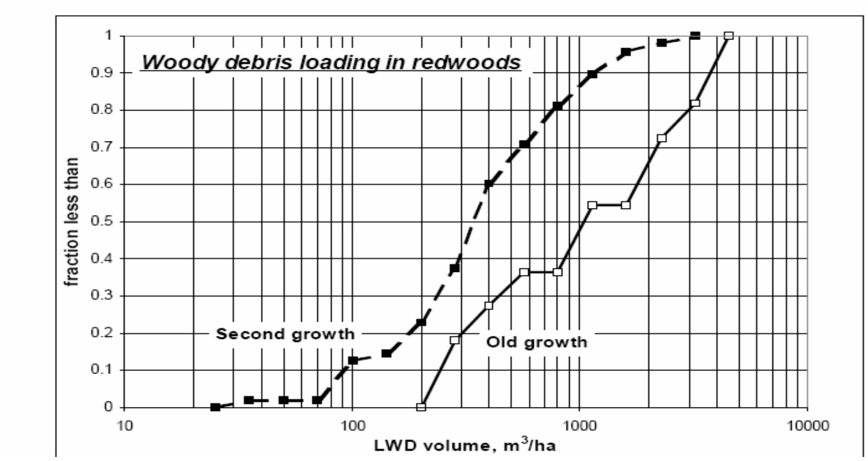
A)



B)



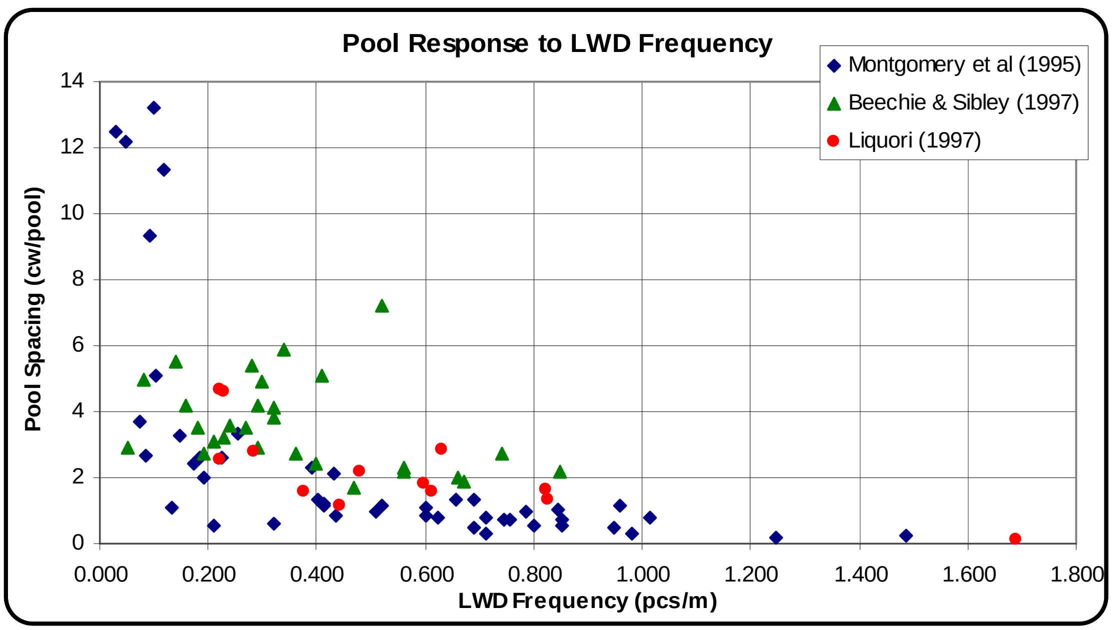
C)



The reviewed literature (Gregory et al. 2003; Hassan et al. 2005; Lassettre and Harris 2001) also emphasize the positive role of wood on aquatic habitat formation. But none of the reviewed papers supply specific quantitative relationships between riparian forest conditions, wood supply, and abundance and quality and abundance of fish habitats (other than pool frequency).

Several field studies (Montgomery et al. 1995, Beechie and Sibley 1997, Martin 2001) have documented how pool spacing and sediment storage are coupled to in-stream wood storage. In general, more instream wood equals more pools and enhanced sediment storage up until a point of about 650 pieces/mile of stream (~400 pieces/km) (Figure 5), at which point wood loading appears to have declining additional effect on pool density (Montgomery et al.1995; Beechie and Sibley 1997; Liquori 1997).

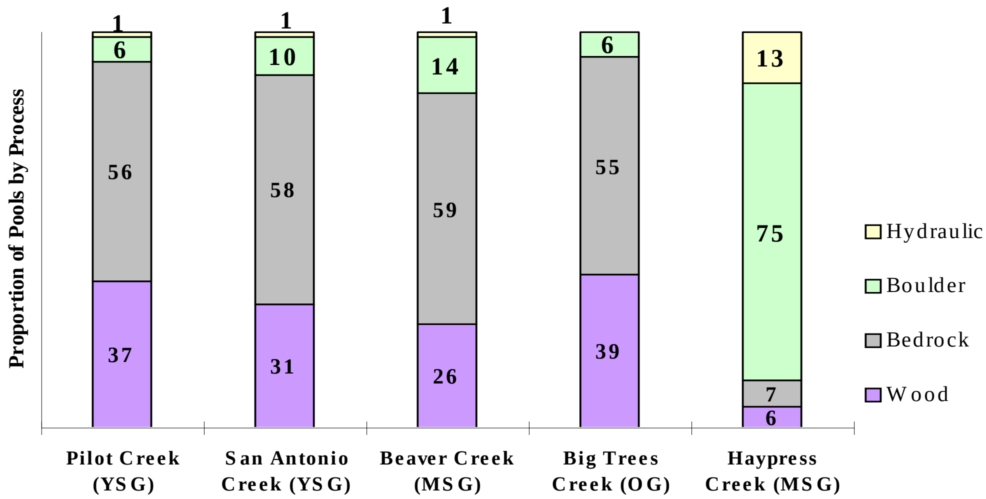
Figure 5) pool density as a function of wood loading in Pacific Northwest streams (developed from data available in Montgomery et al.1995; Beechie and Sibley 1997; Liquori 1997).



Studies in the Pacific Northwest have found that generally, steep and confined streams are significantly less responsive to woody debris inputs than shallow unconfined streams (Rot et al.2000; Montgomery and Buffington 1997). However, other studies of wood in California streams have documented the significant role of wood on pool formation (Benda et al.2003; Benda et al.2004; Benda et al.2005). In the Sierra's, Ruediger and Ward (1996) found no variation in wood loading between stream types, and relatively little geomorphic pool-forming response to wood loading.

In the Sierras also, wood was a relatively minor contributor to pool formation (Figure 6). Reduction of large wood along headwater streams could reduce sediment storage in those channels (May and Gresswell 2003; Jackson et al. 2001).

Figure 6. The proportion of pools formed by different processes is shown for a range of streams in the Sierras in northern California (Benda et al. 2005). Pools are formed by concentrated flow of water acting on the bed. Different instream features are typically attributed to the concentrated flow. In the case of "hydraulic" pools, the concentrated flow is self-formed (i.e. without the benefit of scouring features)



Another factor relating wood recruitment to fish habitat concerns the concept of "Key Pieces". Key pieces of wood are those that form stable structures (such as log jams) in streams and thus create long term pools and areas of sediment storage (Bilby and Ward 1991). In general in northern California, the recruitment of key pieces is driven by bank erosion (Figures 7 and 8).

A problem lies in quantifying an absolute relationship between wood loads and aquatic habitat. A common question posed by managers is "how much wood is enough?". Lisle (2002) considers this problem unsolvable due to the complexities of watersheds and fluvial systems, the variable and stochastic nature of natural systems, and the multifaceted nature of fish habitats (pools, cover, complexity etc). A strictly habitat approach to wood loading shifts the emphasis onto wood loading dynamics of riparian zones and effects of logging on wood supplies to streams, a question that can be informed through wood budgeting (Lisle 2002; MacDonald and Coe 2007). Wood budgets investigate the controls on wood abundance in streams and the effects of forest management on wood input dynamics, an approach that has been carried out along 100-km of streams in California over the past 5 years, and which is summarized in this report

(Benda et al. 2002; Benda et al.2003; Benda et al.2004; Benda et al.2005).

Figure 7. The proportion of key piece recruitment by different processes across the southern Cascades and Klamath Mountains in northern California (Benda et al. 2003).

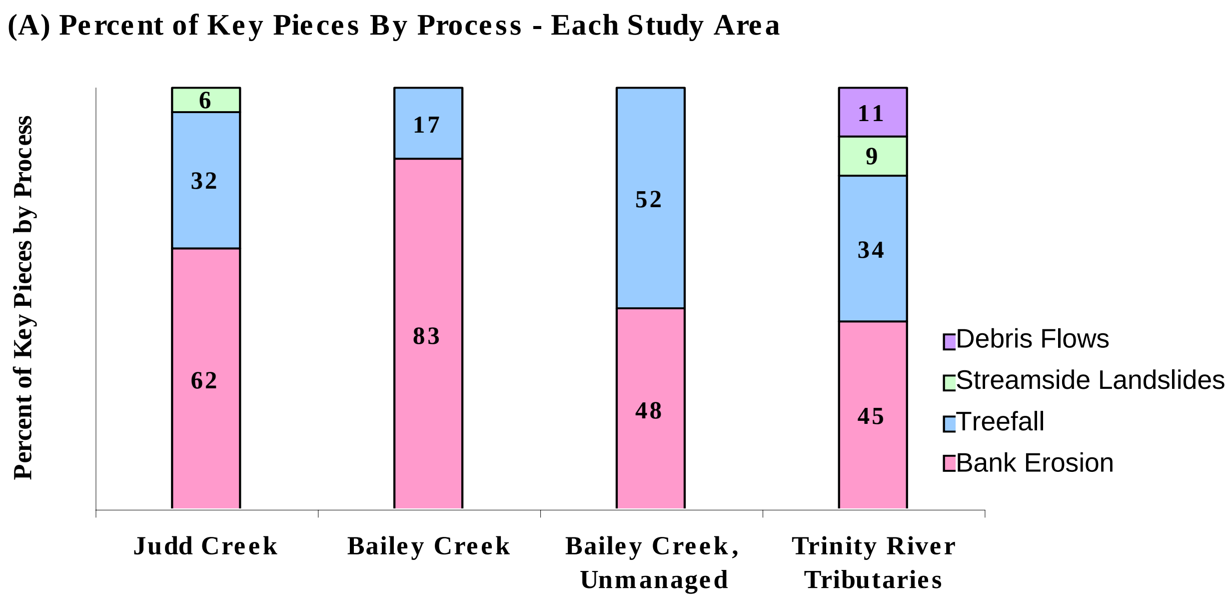
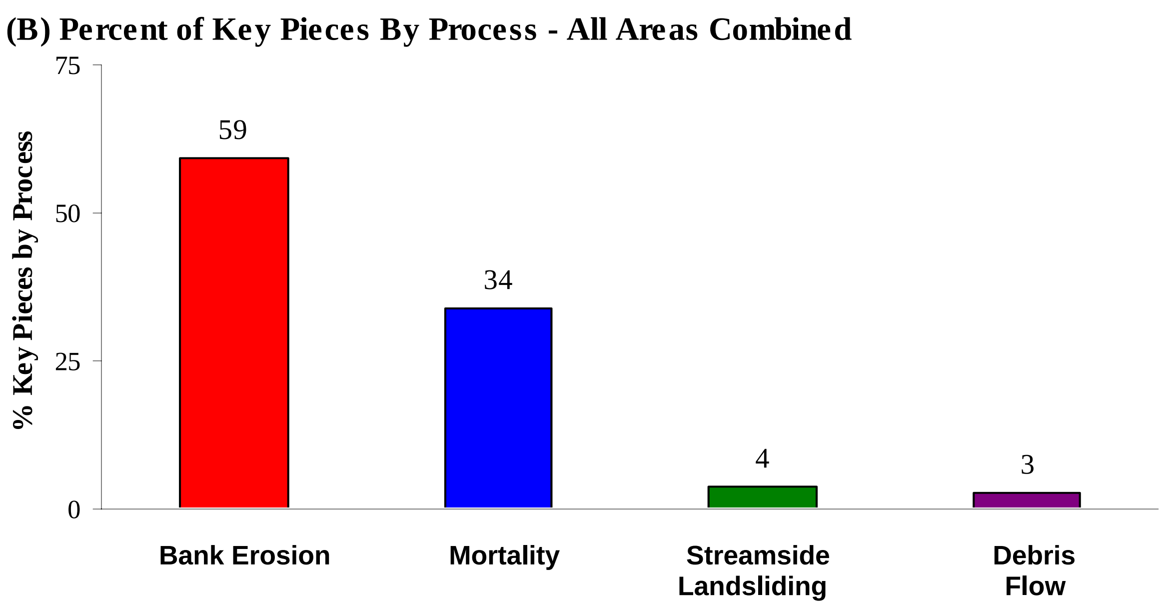


Figure 8. The proportion of key piece recruitment by different processes across the southern Cascades and Klamath Mountains in northern California, all areas combined. Bank erosion is the dominant recruitment agent of large, key pieces of wood (Benda et al. 2003).



WHAT IS THE EFFECT OF NATURAL DISTURBANCE ON THE POTENTIAL RECRUITMENT OF WOOD TO A STREAM?

In the context of the scientific literature, natural disturbances include floods, fires, infestation, disease, windthrow, and landsliding, among others. Many of the reviewed literature papers emphasize the role of natural disturbance as a major wood recruitment agent in streams (Gregory et al. 2003; Hassan et al. 2005; Lassettre and Harris 2001). The emerging science argues that disturbance is a natural and important mechanism for the development and long-term maintenance of diverse and productive riparian and instream habitats (Young 2001; Bisson, Rieman et al. 2003; Nakamura and Swanson 2003; Rieman et al. 2003; others).

Using a wood recruitment model that simulated the role of natural disturbances in the form of landslides, debris flows, and wildfires, Benda and Sias (2003) and Benda et al. (2003) showed that wood loading in streams strongly influenced by the frequency, magnitude and type of disturbance. Landslides and debris flows can be an important source of wood to channels and its specific importance depends on the temporal frequency of failures and spatial density of landslide sites (Nakamura and Swanson 2003). The role of wildfires depends on the frequency and intensity of fires; higher frequency of stand replacing fires in semi arid areas can lead to higher proportion of fire-related wood in a wood budget (up to 50%) (Benda and Sias 2003). Similarly, some studies have found that buffers alter wind patterns that strongly influence the rates of delivery for large woody debris (Surfleet and Ziemer 1996; Bragg and Kershner 2004; Liquori 2006).

A common theme in the reviewed literature is a shift in recognizing that forested watersheds are dynamic systems dependent on conditions in riparian zones that support natural rates and types of disturbance (Bisson, Rieman et al. 2003; Bragg and Kershner 2004; Kobziar and McBride 2006; Ellis 2001; Nakamura and Swanson 2003; Rieman et al. 2003; others). Specific studies and data are limited on this topic, and opinions vary widely. One widely held concept in the reviewed literature is that a sufficiently wide riparian zone that allows riparian areas to grow without management interference can provide conditions where natural disturbance regimes support normal seral development (Lisle 2002; Reid and Hilton 1998; Spence et al. 1996). However, there is a growing sense that human activities (including fire suppression, various land-use practices and forest management) inevitably affect the rates of natural disturbance, and that consideration and mitigation of these affects might be appropriate to promote riparian functions (Dwire and Kauffman 2003; Reeves et al. 2003; Nakamura and Swanson 2003; Kobziar and McBride 2006; others).

Fire

Fire plays a significant role toward direct and indirect contributions of wood to streams (Benda and Sias 1998; Nakamura and Swanson 2003; Rieman et al. 2003). Direct contributions typically come from fire-driven mortality in streamside areas. However, fire also plays an important role in shaping the characteristic disturbances that affect stand growth and dynamics.

Dendrochronological evidence indicates significant and consistent historical fire influence on riparian vegetation structure and composition (Olson 2000; Russell and McBride 2000; Skinner 2001; Everett et al., 2oo3). Yet, modern forest management practices have not yet found an effective approach in managing fire risk in riparian areas. (Debano and Neary 1996; Dwire and Kaufman 2003; others). Fire suppression practices and upslope timber harvest practices have altered rates and characteristics of fire behavior in such a way that natural fire disturbance patterns appear to be substantially altered (Figure 9).

Figure 9. An example in California's Sierras of a wildfire that preferential burned through a riparian area. In this event, fuel loads were higher in the riparian zone compared to the upland forests (courtesy of Dr. Jim Agee).

For example, fire suppression has increased fuel loading in riparian areas in a way that substantially increases the risk of catastrophic crown fires, often in landscapes that naturally experienced frequent low intensity underburns (Hemstrom and Franklin 1982; Barrett 1988; Morrison and Swanson 1990; Camp et al, 1997). While we did not review any specific studies of the effects of riparian crown fire, we suspect that the effects would not benefit salmonids, as crown fires remove canopy coverage, dramatically affect both short-term and long-term wood loading, increases sedimentation in streams, etc.

Some studies are beginning to recognize that fire was historically a predominant mechanism for wood recruitment and riparian stand development, and that the role of fire has changed substantially in recent decades. Although no field studies in the identified literature documented the role of wildfire in wood recruitment, widespread tree death and post fire toppling of trees should lead to increased short-term wood loading in streams.

Flooding

Floods that trigger bank erosion and recruit trees to streams can be a important disturbance agent across all areas and leads to pulsed wood recruitment (see Keller et al. 1995; Swanson et al. 1998; Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005; Hyatt and Naiman 2001; Marcus et al. 2002). Floods can also expand the zone of potential recruitment in large, braided, or avulsing rivers.

Wind

While wind risk is generally perceived to be low in California, wind can affect riparian buffers along clearcut boundaries, primarily along coastal regions (Surfleet and Ziemer 1996; Lisle and Napolitano 1998; Ried and Hilton 1998; Martin 2001; Liquori 2006). Riparian stands grow in conditions that are not exposed to significant wind stress. When exposed suddenly, the root systems often cannot absorb the additional wind stresses following clearcutting, sometimes resulting in a large proportion of buffers experiencing wind-driven treefall. Such windthrow can offer short-term benefits in some systems (Lisle and Napolitano 1998) and minimal benefits to others (Liquori 2006). However, in some cases, such benefits might come at the cost of reduction in recruitment potential over the next 30-50 years (or until the next cohort of trees achieves a functional size relative to the stream).

Increased blowdown mortality and a preferential fall direction to the stream within streamside buffers indicate that wood loading could be higher in managed forests with buffer strips (Martin 2001). Windthrow has also been reported to knock over adjacent trees in a domino-like fashion (Reid and Hilton 1998). Liquori (2006) documented a 72-fold increase in recruitment from windthrow as compared to chronic (competition) mortality estimates in buffer strips along low- to mid-order fish-bearing channels in western Washington. Additionally, the observed wood loading increased to streams within most buffers since fall directions were preferentially directed to streams. Risk of blowdown in this study was strongly correlated to tree species.

Landslides

Streamside landslides, and to a lesser extent debris flows in headwater streams in several of California's physiographic regions (e.g., Coast Ranges, Klamath Mountains) can deliver wood to streams and comprise up to 50% of the total wood load to streams (more commonly 10 – 30%) (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005). Other studies outside California support this general principle (Reeves et al. 2003, Benda and Dunne 1997).

2) Management Influences on Wood Recruitment

The reviewed literature suggests a broad agreement that there are distinct differences between managed and unmanaged forests in the recruitment and wood production into riparian systems. Most studies show that timber harvesting in upslope and adjacent forests can directly affect wood input (Swanson and Leinkaemper 1978; Bilby and Bisson 1998, Rieman 1998). Several studies have documented that downed wood derived from managed forests are smaller in diameter and have less volume than in unmanaged forests, contributing to lower instream loading in logged streams (Bilby and Ward 1991; Ralph et al. 1994). However, virtually all the studies compare relatively young managed forests to substantially older unmanaged forests. Studies generally have not compared managed forests against unmanaged forest of similar ages, so it is difficult to determine the extent that management alters wood production and recruitment processes.

The following discussion seeks to outline ways in which managed forests alter that natural riparian stand dynamics and wood recruitment processes necessary to support instream wood loading conditions.

In many ways, management of forests and fishes are both dependent upon the restoration of natural processes that create diverse and productive ecosystems (Nakamura and Swanson 2003; Rieman et al. 2003). Recovery will generally require better integration of a common ecologically-based conceptual foundation, as well as improved attention to the landscape and ecological context.

This section addresses the ways that management affects wood growth (Section 1.4.2.1) and wood recruitment (Section 1.4.2.2) in riparian areas.

HOW DOES FOREST MANAGEMENT AFFECT WOOD PRODUCTION (I.E. TREE GROWTH) IN RIPARIAN AREAS?

There was limited information in the reviewed literature about the production (i.e. growth) of wood that can be recruited to the stream. However, it is widely accepted that mature and late-seral stands experience slower growth than younger stands, and that stand structure strongly influences the rate of growth within the stand (Oliver and Larsen 1990; Franklin et al. 2002).

The abundance and distribution of dead wood and in-stream wood production in a forest is strongly controlled by disturbance history and stand growth dynamics. Old forests typically accumulate relatively large amounts of dead wood because the debris accumulates over many decades, and decays slowly. By contrast, higher amounts of woody debris are usually generated from young forests following disturbances that kill overstory trees (Spies et al. 1988). However, wood recruitment from small diameter trees does not persist in the stream as smaller trees decay faster (Bilby et al. 1999). Consequently, the greatest difference in the structure of managed vs. older natural forests is that the young riparian stands associated with managed landscapes have greater stems per acre consisting of much smaller diameter wood.

Forest management adjacent to or within the riparian zone can lead to a decrease of in-stream wood recruitment by changing the competitive advantage through above and below ground competition. Acker et al. (2003) studied tree composition, stand complexity, and temporal patterns of tree mortality and found that the variability in tree diameters, tree life-form diversity, and tree species diversity to be important variables affecting stem mortality rates. Wood production and recruitment was much higher from stands where forest management activities changed the dynamics of intra-tree competition and stand dynamics. Therefore, the type of forest management appears to influence the role of tree growth, tree life-form diversity, and tree species diversity on wood recruitment and production.

Riparian wood production is closely linked to riparian structure (e.g. foliage distribution, crown attributes) or the potential to produce other features (e.g. dead wood of different sizes). Disturbances and forest management activities like thinning can lead to a reduction in canopy leaf area, resulting in an increase in the penetration of radiation and precipitation to the forest floor, often leading to the establishment of an understory cohort of new trees (Oliver and Larson 1996). This ingrowth potential is something that most studies of future wood loading ignore because: a) science currently lacks the ability to predict stocking of ingrowth, and b) many scientists studying wood recruitment processes (e.g. hydrologists and geomorphologists) are often not familiar with the principles of stand dynamics. Yet, it is a natural mechanism by which riparian stands evolve.

During the period after thinning events (either thru management or disturbance), nutrient and water uptake will increase per unit of leaf area. Additional light penetration generally increases photosynthetic rates in the lower canopy and additional access to water and essential minerals means plants allocate proportionally less carbohydrate to roots. For these reasons, the rate of wood production per unit of leaf area typically increases (Mattson and Addy 1975). Under careful forest management, the residual stand structures are typically more vigorous, expressed through significantly increased diameter and height growth as well as potentially increased ingrowth (depending on the level of thinning). However, these benefits come at the cost of reduced competition mortality (and thus short-term treefall recruitment) as the existing stand expands into the newly available growing spaces. Such reductions in stem mortality can last a few years to a few decades. During this time of reduced competition mortality, tree recruitment from disturbance processes (e.g. bank erosion, landslides, floods, wind, ice/snow damage, etc) will continue to provide woody debris recruitment.

Riparian forest conditions substantially influence wood loading in streams (Bragg et al. 2000; Liquori 2000). While tree removal from riparian areas can reduce the number of trees that can be recruited, forest silviculture practices can improve the quality and size of riparian trees by improving tree growth, selecting for preferred species, affecting rates and timing of competition mortality, and disturbance regimes (e.g. fuel loading, insect infestations, disease). Riparian species typically have a large array of survival strategies that support growth and recovery from disturbances (Dwire and Kauffman 2003).

Wood recruitment models (Benda & Sias 1998; Bragg & Kerschner 1997; Bragg & Kerschner 2000; Gregory et al. 2003; Bragg & Kerschner 2004; Welty et al. 2002) have been used to evaluate the future potential of wood production in riparian zones. Some studies suggest that models are useful because they provide objective, scientific tools that can be used to evaluate various responses to management treatment. However, many of the wood recruitment models use forest growth simulators that were developed for very different management purposes that might not be entirely suited for predicting riparian response (Bragg et al. 2000; Welty et al. 2002). Forest growth simulators are calibrated from upland stands that are specifically selected to minimize natural variability while riparian stands are typically quite diverse (Welty et al. 2002). Additionally, model results often imply that any tree removal will reduce wood loading over time. However, existing models do not account for ingrowth (new trees that germinate in response to opening the canopy), which can increase total wood production over a given period, and can affect future wood loading in thinned forests. They also poorly account for depletion (decay) or breakage, and thus are not yet fully predictive (Gregory et al. 2003). Models also have limited capacity to account for disturbance processes in terms of how disturbance can affect mortality and growth.

Ecologically-driven objectives for manipulating riparian stand structure can include: improving riparian tree growth, affecting the timing of competition mortality periods, mitigating for significant disturbance risks, redirecting successional trajectories, species conversion, and targeting other desired riparian stand conditions (Welty et al. 2002; Ligon et al. 1999). Such treatments could have significant benefits to aquatic ecosystems in certain settings, although such treatments might require compromises between short-term and long-term wood loading potential. Silvicultural methods and tools are available that can help guide such objectives.

It is important to note that responses to riparian forest management are sensitive to the varied site conditions. Each riparian ecosystem will respond differently to treatments, depending on the forest properties, site productivity, stream conditions, and the effectiveness of management (Bragg and Kershner 1997).

HOW DOES FOREST MANAGEMENT AFFECT IN-STREAM WOOD DELIVERY TO CHANNELS?

There is almost universal consensus that unrestricted clearcutting to the waters edge in fish-bearing streams is clearly detrimental to aquatic environments. In the absence of clearcutting, forest management in or near riparian zones can be beneficial, detrimental, or both, sometimes at the same site.

Management can affect the frequency and magnitude of natural recruitment processes associated with disturbance (Dwire and Kauffman 2003), and can influence the successional pathways, species composition, and structure of the stand in ways that affect growth and competition mortality (see above). Management in headwater areas can also affect the natural landslide regime in ways that affect wood delivered from landslides and debris flows by affecting hillslope pore pressures, root reinforcement, hydrologic impacts, sediment loading, and wood loading on the hillslopes (Ziemer 1981; Dietrich et al. 1986; Torres et al. 1998; others). Landslide rates have historically increased in response to forest management (Bishop 1964; Robison et al. 1999; Gomi et al. 2001; Miller et al. 2003; Cafferata and Munn 2002; Gomi et al. 2005; Hassan et al. 2005; others). It is possible that there might be implications for future wood recruitment as: a) forest management practices reduce the rate of landsliding, and b) fewer available source areas are prone to sliding (since the pressures have been reduced over the last 50+ years). The extent that this is an issue could not be explored, as the literature to support such an analysis was not the focus of this review.

Both theoretical (model based) and field based studies demonstrate that younger stands have smaller trees (in both height and diameter) and therefore have lower in-stream wood potential relative to larger, older stands (Benda and Sias 2003, Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005, Bragg et al. 2000). Stands with identical recruitment rates and processes will experience different wood recruitment volumes based on the available height, diameter and density of riparian trees. Legacy forest practices continue to affect instream wood loading conditions. Instream wood loading conditions are low along many (probably most) 2^{nd}-growth forests along the Coast Range (Wooster and Hilton 2004). It is difficult to determine the extent that wood delivery rates are different between old-growth and 2^{nd}-growth, since many studies report wood volume (not pieces), which is substantially higher in older stands due to the difference in tree sizes. Some studies report higher wood delivery rates from managed stands, but lower total wood volume. Older, taller trees can also deliver wood from farther distances, increasing the area that can deliver woody debris. In addition, taller trees can increase the proportion of wood that is derived from treefall compared to bank erosion (Benda et al. 2005) because of the larger potential source area for treefall.

There are several common themes associated with forest management effects on wood recruitment. These include:

- Legacy effects
- Altered short-term supply
- Altered long-term supply
- Altered susceptibility to disturbance
- Altered timing of competition mortality

Legacy Effects

Historic logging practices have had lasting impacts on aquatic systems. Such "legacy" practices can affect existing conditions in ways that range from severe to subtle. Legacy effects are not equally significant in all regions of California. The coastal legacy included stream cleaning and instream yarding. Inland legacies might also exist, but can be more subtle. Some inland areas were "hi-graded" which resulted in poor stocking quality during subsequent forest regeneration. To a certain degree, fire suppression activities in recent decades can also have resulted in legacy effects. Fire frequencies have decreased in many California forests, increasing fuel loading and risk for high intensity crown fires. Riparian areas have not been immune to such activities.

Early practices in the 19th and early 20th Centuries along the coast included not only logging in riparian areas, but yarding logs through the stream corridor (often within the stream itself). Early "splash dams" held logs in ponded areas for sudden release in the form of a manufactured flood. Such floods dramatically scoured the stream and riparian areas, leaving substantial geomorphic effects than can still be observed today.

Early logging practices also included large clearcuts over entire watersheds. Large floods following such disturbances had impacts on stream channels, often causing incision, channel migration and widespread channel erosion. Early clearcut logging practices on steep slopes also increased rates of landsliding and other mass wasting processes in ways that: a) increased sediment load to aquatic environments; and b) altered the natural frequency and magnitude of landsliding, affecting future landslide risks (and potentially the distribution of wood loading from landslides) (Benda and Dunne 1997).

Even as recent as the 1980s, active instream restoration practices along the coast promoted and funded by State agencies involved wholesale removal of instream woody debris, a practice referred to as "stream cleaning" (Berbach 2001; Wooster and Hilton 2004). The mistaken perception was that instream wood loading created passage impediments for fish.

Buffers in California were first mandated with the passage of the modern Forest Practice Act in 1973 (and enforced on the ground in 1975). Early rules were focused on temperature functions, often to the exclusion of wood functions. On the coast, riparian timber harvest under the Forest Practices Act practices was common, often removing all conifer trees next to streams. Inland areas were more prone to temperature risks, so practices requiring canopy closure can have given preference to conifers in riparian zones, resulting in long-term depletion of riparian hardwood stands. These practices ended when the current T&I Rule Package was implemented in 1999, and a broader set of functional controls were required.

As a result of these and other legacy practices, riparian areas that are found in lands that have been managed for more than 20 years or so will typically have some legacy effects that have altered the riparian environment. In some cases, the alterations can be easily detected. For example, many coastal riparian stands are stocked with relatively young riparian trees (as compared to old reference stands). Other legacy effects can be more subtle, like increased fuel loads and altered fire regimes, or altered landslide regimes.

Altered Short-Term Supply

Timber harvest that removes all or some of the trees within a zone one tree height of the channel will reduce the number of trees that can potentially recruit to streams (Bragg and Kershner 1997; Welty et al. 2002). The width of the zone is dependent on tree age to the extent that height is related to age (McDade et al. 1990). However, because the probability of tree recruitment increases non-linearly towards the stream and bank erosion is a major wood recruitment agent, the reduction is much smaller if areas closest to the stream are not harvested. In many California streams, 80 to 90% of wood recruitment comes within a zone 30 to 100 feet (10 to 30 m) of the channel edge (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005).

Wood loads in buffered streams adjacent to clearcuts increase relative to unharvested streams (Surfleet and Ziemer 1996; Liquori 2006), primarily in response to increased susceptibility of windthrow and other disturbances. Yarding slash has also been shown to increase wood loading in the short-term. Certain types of historical logging increased wood storage in streams if wood debris (slash) was left in channels (Jackson et al. 2001; Benda et al. 2002; Benda et al. 2004).

Altered Long-Term Supply

Silvicultural treatments in riparian areas can increase the diameter growth in riparian areas, which can increase the rate of recovery for streams requiring large diameter wood (Welty et al. 2002). Clearcutting riparian zones areas can lead to greatly reduced wood loading for 50 to 100 years following harvest (Bragg et al. 2000;

Benda and Sias 2003; Hassan et al. 2005). Many models also predict that long-term recruitment is diminished by any tree removal from riparian zones, although most models have at least one or more challenges with accurate long-term predictions (Gregory et al. 2003).

Models are the only available tool for projecting future wood recruitment potential. Wood recruitment models have been used to investigate the implications of various riparian management regimes on the recruitment of wood to streams (Rainville et al. 1986, Van Sickle and Gregory 1990, Beechie et al. 2000, Bragg et al. 2000; others). Models use upslope growth and yield relationships because such relationships are not available in riparian zones. Models also cannot accurately predict ingrowth (new stems that germinate or suppressed stems that experience rapid growth). In-channel processes such as tree entry breakage and log breakage, movement, depletion and decomposition are poorly understood, yet many models are very sensitive to these variables. Models that have incorporated these variables have used simplified assumptions (Murphy and Koski 1989; Beechie et al. 2000; Bragg et al. 2000). Transport of wood from upstream sources has either been ignored or has been assumed to equal output of the reach for a given time interval (Murphy and Koski 1989; Van Sickle and Gregory 1990).

Altered Timing of Competition Mortality

Stand conditions affect the growth and mortality dynamics in riparian stands in a manner that affects wood recruitment (Liquori 2000). Some forest management activities (e.g., thinning) can reduce short-term rates of competition mortality while increasing stand growth. Other activities (e.g., prescribed fire) could increase short-term mortality and reduce long-term competition mortality. For example, in the redwood forest zone, timber harvest that initiated a new stand of trees can lead to increased forest mortality rates compared to the reduced rates in old growth redwood forests (Benda et al. 2002).

Altered Susceptibility to Natural Recruitment Processes

Forest management alters the very patterns of growth and disturbance that influence riparian conditions and functional responses. Forest management activities affect fire regimes, wind patterns, landslide patterns, and stand growth dynamics in ways that also affect riparian structure and function. Riparian, aquatic and upland ecosystems are linked and dynamic, and our understanding of these interactions is still developing (Bisson, Rieman et al. 2003). In many cases, the over-generalized nature by which management establishes practices can compromise ecosystem resilience (Rieman et al. 2003).

Where debris flows in low-order headwater streams are a wood recruitment process (mostly in California's Coast Ranges and Klamath Mountains), harvest of trees along headwater channels and hollows could reduce that source of wood to larger fish-bearing streams (Reeves et al. 2003, May and Gresswell 2003; Benda and Dunne 1997). However, typically only a portion of trees delivered from these sources are effective as woody debris. Where timber harvest or road construction change the likelihood of landsliding and debris flows in headwater channels, then wood loading supplied by these processes will also be changed. Legacy forest management practices dramatically increased rates of landslides and debris flows (May and Gresswell 2003). Modern practices seek to minimize these processes, and that will certainly affect the recruitment dynamics in some landscapes.

Riparian buffers can also affect the preferred direction of treefall, potentially resulting in a significant and substantial increase in trees falling toward the channel (Liquori 2006) than would be predicted by a purely random treefall assumption (Robison and Beschta 1990b). Many of the wood recruitment models are quite sensitive to treefall direction (Bragg and Kershner 2004), yet in the absence of fall direction data, most models apply the random treefall model, and thus can underpredict the delivery of wood. Treefall bias toward the channel can deliver up to 3 times more wood from the riparian stand when compared to random fall directions (Van Sickle and Gregory 1990; Bragg and Kershner 2004; Liquori 2006).

Creating buffer strips along streams could lead to accelerated mortality in the buffers due to increased blowdown (Lisle and Napolitano 1998), most likely along the north coast area, where winter storms can yield strong winds. This could lead to a tree mortality rate orders of magnitude higher compared to suppression mortality alone in natural forests (Liquori 2006).

Under some circumstances, such as dry pre-fire climatic conditions and the accumulation of dry fuel, riparian areas become corridors for fire movement (Pettit and Naiman 2007). Riparian areas tend to have higher growth and biomass accumulation as compared to upland stands (Agee 1999). Riparian zone fuel loadings are influenced by fire suppression and exclusion. Ladder fuels in the form of shrubs and understory plants bridge these riparian surface fuel loadings to highly flammable overstory fuels. In contrast to upland forests, the geomorphology and hydrologic features of riparian corridors typically result in a greater dominance of shrubs and deciduous trees. Depending on the regional microclimate, these understory and deciduous trees can either contribute to crown-fire behavior or retard the spread of fire through moister and cooler microclimates with higher levels of both live and downed fuel moisture contents (Dwire and Kaufman 2003). Fire suppression that reduces fire occurrence in riparian zones might reduce wood loading to streams over the long term since in semi-arid Mediterranean areas wood recruitment by fire can be substantial (Young 1984; Benda and Sias 2003). Stand-replacing riparian fires can occur preferentially within riparian zones that have not been burned or thinned to reduce fuel loads (Murphy et al 2007). Although there are several recent papers reviewing different aspects of wildfire in riparian areas (Bisson, Rieman et al. 2003; Dwire and Kauffman 2003; Raiman et al 2003; Reeves et al. 2006; Pettit and Naiman 2007), there is general agreement that there is much to be learned concerning fire in these environments.

In parts of California where the lack of disturbance has contributed to heavier than normal surface and ladder fuels, riparian zones can lead to altered fire behavior in riparian systems. In several recent examples (e.g., Angora, Trabing, Antelope fires), wildfires entering the riparian zones have exhibited higher intensities than upland zones, creating fire "wicks" where behavior crowns and "runs" around or through fuel treatments by moving upslope through the riparian zone (Murphy et al. 2007). Based upon these observational reports and studies, it is difficult to ascertain the exact nature of how riparian management (or lack thereof) can change the susceptibility to disturbances like high-intensity, stand-replacement wildfire events.

3) Factors Affecting Buffer Design

There are two broad strategies for maintaining riparian functions in forested landscapes. The specific factors that are important depend on the strategic policy direction that guides management.

One strategy is to buffer streams with large riparian reserves to minimize the disturbance in the riparian zone so that riparian stand conditions can evolve naturally. Support for this approach is described in several papers (FEMAT 1993; Spence et al. 1996; Reid and Hilton 1998; others).

Another strategy is to directly manage aquatic functions, often at landscape scales (e.g. watersheds) to promote ecological processes and functions that can be affected by forest management practices. This approach typically calls for integrated management strategies that respond to the dynamic and varied ecological context that exists over the landscape. Support for this approach is also provided in several papers (Kobziar and McBride 2006; Naiman et al. 2000;

Nakamura et al. 2000; Dwire and Kaufman 2003; Everett et al. 2003; Rieman et al 2003; Thompson 2006; others). Often, this latter approach focuses on minimizing major disturbances in favor of the types of smaller (often more frequent) disturbances that support ecosystem processes.

This section addresses some of the thoughts expressed in the literature about how to design riparian buffers.

WHAT CHARACTERISTICS OF RIPARIAN BUFFER ZONES AFFECT THE PRODUCTION OF POTENTIAL IN-STREAM WOOD AND HOW SHOULD FOREST MANAGEMENT GOALS DIFFER BY STREAM ORDER, VEGETATION TYPE, AND REGION TO DELIVER WOOD TO THE STREAM OF THE APPROPRIATE DIAMETER SIZE, SPECIES AND OTHER CHARACTERISTICS TO MAINTAIN SALMONID HABITAT OVER SPACE AND TIME?

Salmonids clearly benefit by higher levels of wood loading. Wood loading creates pools, regulates sediment transport processes, helps to sort gravels into spawning sites, provides cover, and provides a substrate for macroinvertebrate production (Cederholm et al. 1997; Montgomery et al. 1995; Beechie and Sibley 1997; others).

Many streams in California are depleted in wood loading as a result of legacy forest and stream management practices (Wooster and Hilton 2004). Recovery of this depleted condition will require both more wood recruitment and increased tree diameter growth. Natural recovery of wood loading conditions could take a century or more (Bragg and Kershner 1997; Hassan et al. 2005). Management activities in some riparian stands can potentially reduce this recovery time while promoting ecological diversity and quality salmonid habitat conditions by:

- Using silvicultural strategies to affect growth and mortality dynamics (Welty et al 2003; Bragg and Kershner 1997)
- Managing the risks of disturbance to encourage relatively frequent, low-intensity disturbances over larger, high magnitude disturbances (Kobziar and McBride 2006; Naiman et al. 2000; Nakamura et al. 2000; Dwire and Kaufman 2003; Everett et al. 2003; Rieman et al 2003; others).
- Balancing the trade-offs between various exchange functions as driven by limited biological factors. For example, identifying sites where other functional objectives might be locally more

important biologically than wood recruitment objectives (see Chapters 2 and 7).

We suggest that riparian silvicultural objectives that would support ecological functions important to salmonids (and other fauna) would seek to balance competition mortality objectives with growth objectives or other exchange function objectives based on a diagnosis of site requirements. For example, a site with low wood loading might seek to shift the balance toward promoting mortality of desired species. Similarly, a site with riparian tree diameters that are too small to support ecological functions might encourage stem growth in a manner that can reduce the time required to achieve a functional diameter, perhaps by several decades (Bilby and Ward 1989; Welty et al. 2002). Silvicultural science has developed a number of tools for manipulating forest stands to meet specific management objectives, and such tools are not necessarily restricted to maximizing timber yield.

Several key factors affect riparian community composition and structure. These include several that cannot be manipulated easily, like climate, landform, and soil types (Naiman et al. 1998; Rot et al. 2000; others). Other major factors to consider in the design of riparian buffers for in-stream wood production are:

- Existing Stand Density, Composition and Structure (Bragg et al. 2000; Franklin et al. 2001; Welty et al. 2002; others)
- Stream Type, Order and Watershed Context (Bilby and Likens 1980; Bilby 1984; Lassettre and Harris 2001; Young 2001; Wing and Skaugset 2002; Rieman et al. 2003; others)
- Vegetation Type and Soil/ Site Index (Oliver and Larson 1996; Franklin et al 2001; Welty et al. 2002; others)
- Regional Context (Ruediger and Ward 1996; others)
- Disturbance Context (Nakamura and Swanson 2003; Rieman et al 2003; others)

As we've described in Section 0, woody debris in streams comes from several major sources, including channel movements, streamside disturbances, tree mortality, streamside landslides, and debris flows in headwater areas. Thus the management of stream channel structure and watersheds might consider all sources of potential wood recruitment when designing site treatments. The buffer design should accommodate the physical and biological stream requirements, long term stand resilience, and disturbance risks. For example, if surface and ladder fuels in the buffer are predisposing the riparian stand to crown/stand replacement fire when the disturbance history does not show any evidence of growth trajectories from this type of stand development, then the buffer design might include some amount of small and/or moderate managed disturbances to break up the fuel continuity, prevent the likelihood of a catastrophic event, and ensure that functional impacts are minimized. Alternatively, if the stream environment requires large trees to function, and riparian conditions consist of densely stocked, small diameter trees, then thinning alternatives designed to promote growth could expedite recovery by a factor of decades (Welty et al. 2002).

The following sections describe some details associated with these factors.

Stand Density, Composition and Structure

In upland stands, there is a direct relationship between stand density, composition and structure, and the growth and mortality dynamics in the stand. We assume that such trends persist in riparian areas, although direct studies are not available to our knowledge. Generally, growth and mortality in forested stands are cyclical, dynamic, and vary depending on the stand composition. Single cohort, single species stands respond differently than multi-cohort, multi-species stands (Oliver and Larson 1996; Noss 2000). When competition mortality rates are high, recruitment tends to increase, but tree growth can vary from very slow in early stem exclusion phases to more rapid growth in advanced stem exclusion phases. Often, growth rates correspond to the amount of available growing space opened up by mortality, regardless of whether the mortality is from competition or disturbances. Such openings in available growing space can take decades under competition mortality, or can be nearly instantaneous in the form of site disturbance processes.

The stand density, composition, and structure will determine the potential for wood production and recruitment. At the stand level, overstory canopy characteristics such as stem density and gap size have been linked to composition and dynamics of tree regeneration (Gray and Spies 1996; Spies 1997). These attributes also change with time, as the stand grows and responds dynamically.

Stand manipulation in support of wood (or other) functions should consider the benefits in shaping the stand density, structure, and composition against the impacts on stem mortality and recruitment.

Two general trends exist for stand development that have relevance to in-stream wood production:

1. A growth trend that follows large disturbances or management activities where tree growth and biomass increase slowly at first, then increase rapidly until trees reach the carrying capacity of the site (based on stem density) and sites reach maximum capacity to support vegetative growth. In this case, growth slows and mortality increases resulting in a pulse of recruitment that can persist for a period of years to decades.

2. The other growth trajectory that typically follows modest disturbances or management activities leads to more rapid growth of residual trees (those that survive disturbance) followed by a period of declining growth as the carrying capacity is reached. In this case, the period of rapid growth is much shorter than the stand-replacing growth period.

The period with the greatest stem losses can occur in even-aged stands between ages of about 50 and 110 years, when stand densities decline from more than 200 trees per acre to about 100 trees per acre or less. At this age, stems are typically large enough to function as instream wood. By contrast, older stands can have stem densities of 15-50 trees per acre. Thus earlier cycles of competition mortality can yield significantly more stems to the stream, although these stems are often of smaller diameter than in older stands (Oliver and Larson 1996).

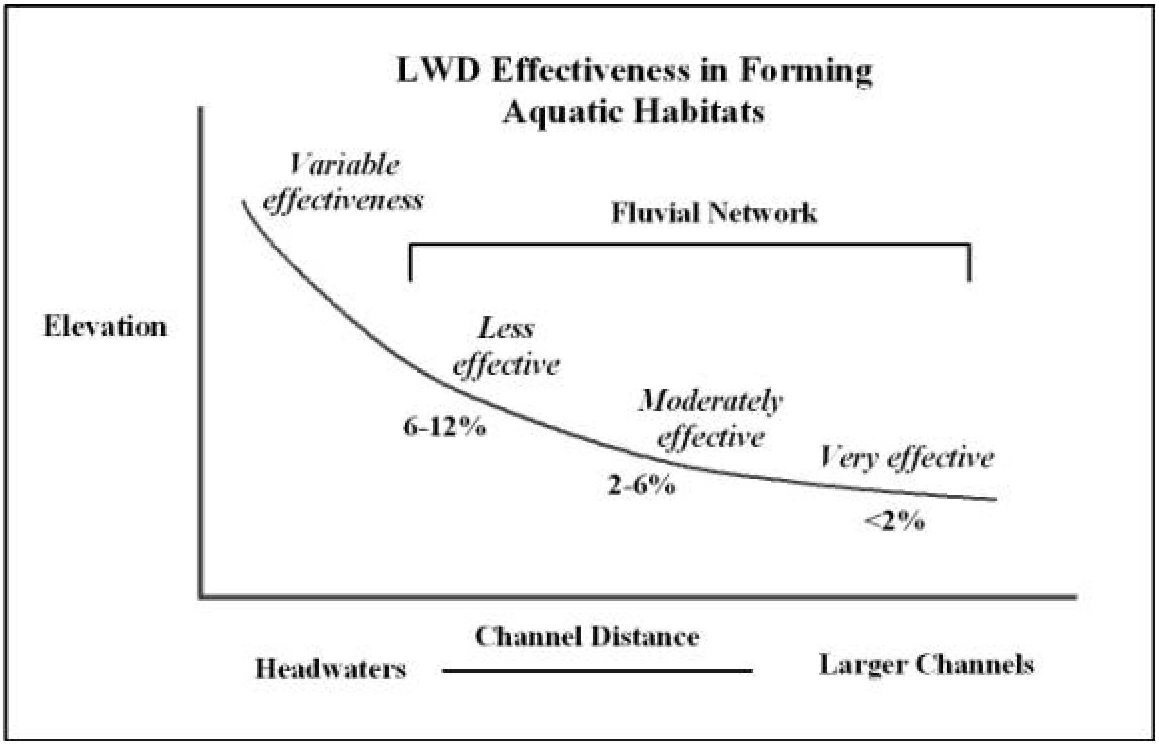
Although individual stands develop in a wide variety of ways, general tendencies allow one to predict the characteristics of one type of forest structure from knowledge of another (e.g. foliage height distributions from tree diameter variation) (Spies and Franklin 1991) and to predict future states of population stands from knowledge of their current forest structure (e.g., knowledge of current size/age distributions and species of live trees can be used to estimate future characteristics of dead trees).

Stream Type, Stream Order and Watershed Context

Wood functions tend to vary by stream type, and thus the qualities and characteristics needed to support those functions varies. Generally, larger streams require large diameter wood (Bilby and Ward 1989), and habitat functions in lower gradient streams are more responsive to wood loading (Beechie and Sibley 1997; Montgomery & Buffington 1997).

The reviewed literature indicates that the relationship between wood and in-stream habitat varies across different stream types in California (Figure 10) (Ruediger and Ward 1996; Berg et al. 1998; Rot et al. 2000; Lassettre and Harris 2001; Benda et al. 2005). Stream order is one type of classification that is helpful in describing the relative scale of stream functions and processes, however, it does not describe other important factors like stream type, confinement, and gradient that has been shown to significantly affect stream processes and functions (Montgomery & Buffington 1997).

Figure 10) Wood effectiveness in providing instream functions for salmonids. In steeper streams, wood is primarily a source of gradient control that acts to trap and store sediment. In lower reaches, wood acts to modify the channel bed and morphology in support of specific life-cycle requirements for salmonids (e.g. spawning, rearing, etc.)



For example, Rot et al. (2000) found significant variation in wood loading and effectiveness in Pacific Northwest plane-bed and pool-riffle channels, and relatively little effect in cascade and bedrock channels. Similarly, Wing & Skaugset (2002) found that channel morphology was more important than land-use in predicting wood function. Ruediger & Ward (1996) found limited geomorphic response in Sierra channels and little variation between channel types. These variations imply that stream type might be more important than stream order in defining the role of wood, although there is a general relationship between stream order and stream types.

Larger-order, lower gradient streams experience channel migration processes that increase recruitment from bank erosion processes (Benda and Sais 1998). Such channels also are prone to wood transport, and wood tends to accumulate in jams that can persist for only a fraction of the lifespan of the wood (Hyatt and Naiman 2001). Recruited conifer wood can exist for several decades to centuries if not transported downstream (Keller et al 1995; Hyatt and Naiman 2001). Typically these systems are more dependent on larger “key pieces” of woody debris that act as structural anchors for jams. Wood volume is a good indicator of effectiveness in these reaches.

Mid-order, mid-gradient streams typically accumulate the largest amount of woody debris, and are typically most responsive to wood loading (Keller et al 1995; Nakamura and Swanson 2003). Effective wood loading in these streams tends to be driven by the number of pieces of wood.

Low-order, steeper channels accumulate wood from logging slash (Jackson et al 2001), competition mortality, and streamside landslides (Benda and Sias 1998). Smaller wood tends to function in these systems (Hassan et al. 2006). Steep, confined channels utilize wood less for habitat, and more for sediment regulation and channel stabilization functions.

These generalizations assume that gradient and order are related, which is not always the case. Small, low-order, low-gradient streams can express behaviors similar to mid- or large-order streams. Similarly, large-order confined channels can express functions more similar to low- to mid-order conditions.

Vegetation Type and Soil/Site Index

Vegetation types strongly affect the quality and quantity of wood recruitment (Hassan et al. 2006). Conifer species are typically preferred for wood loading functions, since hardwoods break down quickly in stream environments, typically within a few years (CBOF-TAC 2007). The vegetation type and soil/site index also affects the site-potential tree height, and thus the scale of the source distance curves (see below and Chapter 7).

Typically, vegetation types that support more wood volume in the riparian stand also tend to support more volume in the stream (Keller et al. 1995). Thus coastal redwood stands have a potential for more wood loading that Sierran Ponderosa Pine.

Regional Context

Regional variation strongly influences the predominant disturbances that are likely to drive wood recruitment processes (Nakamura and Swanson 2003). For example, landslide and debris flow processes are more common in the coast and Klamath landscapes. Similarly, variation in forest types influences wood recruitment rates and processes. For example, redwoods deliver more wood loading and storage than mixed Sierra conifers (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005).

The reviewed literature also suggests that the relationship between wood and in-stream habitat varies across different regions in California. Wood is a major pool former in many coastal and inland areas (Benda et al. 2003; Benda et al. 2004; Benda et al. 2005) but becomes less important in the boulder and bedrock dominated Sierras (Ruediger and Ward 1996; Berg et al. 1998; Benda et al. 2005).

Other than these somewhat obvious relationships, specific regional variation in wood recruitment that would guide streamside protection strategies is not apparent from the literature. While regional variation is important to understand, the literature for California is limited, and thus specific recommendations can only be inferred.

Disturbance Context

As described previously, management practices can directly and indirectly affect the frequency, intensity and magnitude of the disturbance processes that are responsible for recruiting wood to salmonid streams (Nakamura and Swanson 2003; Bisson; Rieman et al. 2003; others). Understanding this context is essential to properly restoring functional riparian conditions in managed landscapes (Rieman et al. 2003). We describe this in more detail in Chapter 7 of this report.

WHAT MINIMUM BUFFER WIDTHS HAVE BEEN SHOWN TO BE EFFECTIVE?

There has been little agreement in the scientific community in defining the *minimum* buffer width necessary to provide sufficient wood recruitment to sustain salmonid habitat (Young 2001; Lisle 2002). One of the reasons that these issues remains unresolved is that there is no recognized ecological endpoint for which individual streams should be managed (Young 2001), and no consensus about how much wood is “enough” to support ecological functions (Lisle 2002). For example, the reviewed literature reports that the maximum width needed to contribute almost all of the woody debris recruitment *from treefall* is 1 tree-height (McDade 1990; Robison and Beschta 1990; others). However, within 1 tree height, there remains a wide variation in responses, due in part to variations in the dominant recruitment mechanisms (Castelle & Johnson 2000; Benda et al. 2002; Benda et a.l 2003; Benda et al. 2005; Liquori 2006). Approaches to address this question have followed several lines of logic.

Some of the reviewed literature have argued for wider buffers to protect the riparian community from direct and indirect disturbances associated with timber harvest (Reid and Hilton 1998; FEMAT 1993; Spence et al. 1996). Others have promoted the use of instream wood loading observation in reference streams to establish targets. Such targets would establish the required width, following the line that higher instream loading targets would require wider buffers (Fox and Bolton 2007; others). Yet others have modeled riparian recruitment processes to identify riparian stand conditions necessary to achieve functional objectives (Van Sickle and Gregory 1990; Bragg 2000; Welty et al. 2002; Gregory 2003; others), and yet others have used empirical data from adjacent riparian stands as a reference (McDade et al. 1990).

A number of investigators have used cumulative source distance relationships to establish buffer widths (McDade et al. 1990; Van Sickle & Gregory 1990; Robison and Beschta 1990; FEMAT 1993; Welty 2002; Liquori 2006). These curves (Figure 11 thru 15) depict the cumulative sources of wood as a function of the distance away from the stream (primarily using mortality as the only recruitment agent), and offer the most robust evidence for effective buffer widths. These papers usually describe distances in the form of a site-potential tree height to account for variation by species and site potential. However, we’ve translated this variable into a distance for the purposes of this discussion. Note that the shape of these curves depends on the wood metric (volume v. trees) as well as the dominant recruitment mechanism.

Figure 11) Source distance relationship originally described in FEMAT.

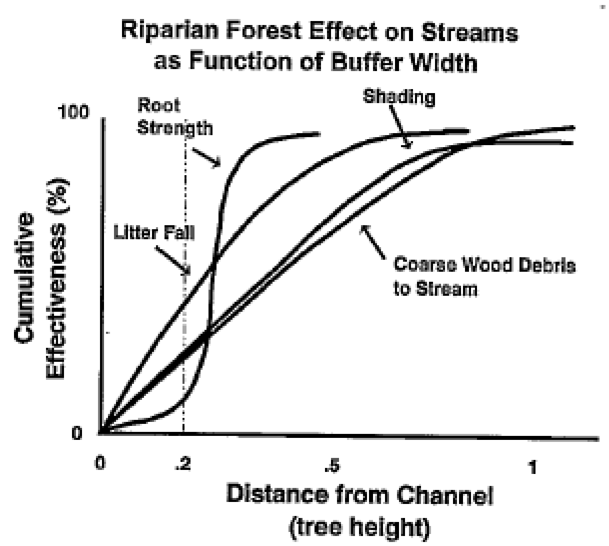
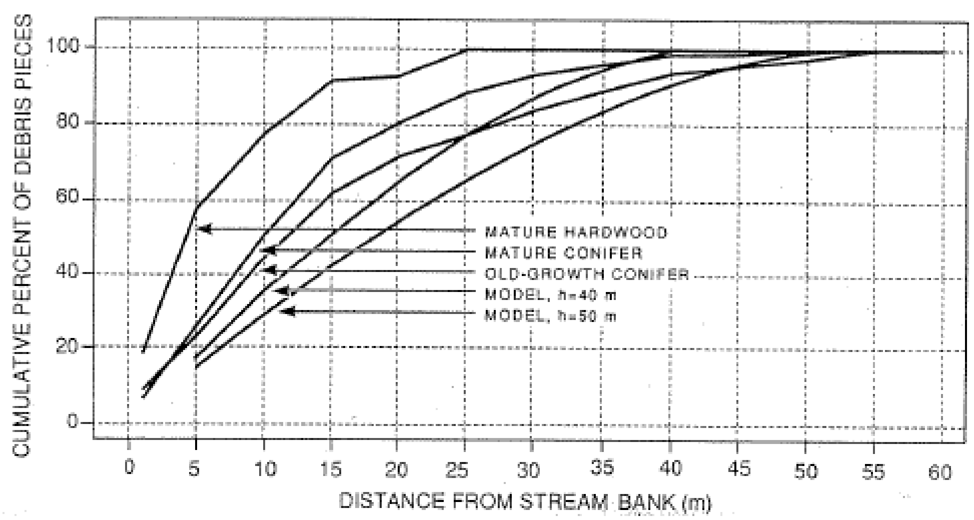


Figure 12) Source distance curves described by McDade et al 1990.



The source distance studies generally report that most (ranging from ~50-95+%) of the potential wood recruitment *from riparian areas* occurs within ~30-100 feet (10-30 m) of the channel. In California streams, 70 to 90% of wood generally originates from with ~30 to 100 feet (10 to 30 m) of the channel (Figures 13-14). Riparian area width beyond 100 ft (30m) had a relatively small effect on wood recruitment functions in most cases (McDade et al. 1990; Van Sickle and Gregory 1990; Robison and Beschta 1990; FEMAT 1993; Welty 2002;

Liquori 2006). Extensive data are available for these relationships; a comprehensive meta-analysis of data from all regions is beyond the scope of this report.

Figure 13) Source distance relationship from Benda 2005. See Chapter 7 for a more detailed discussion of source distances.

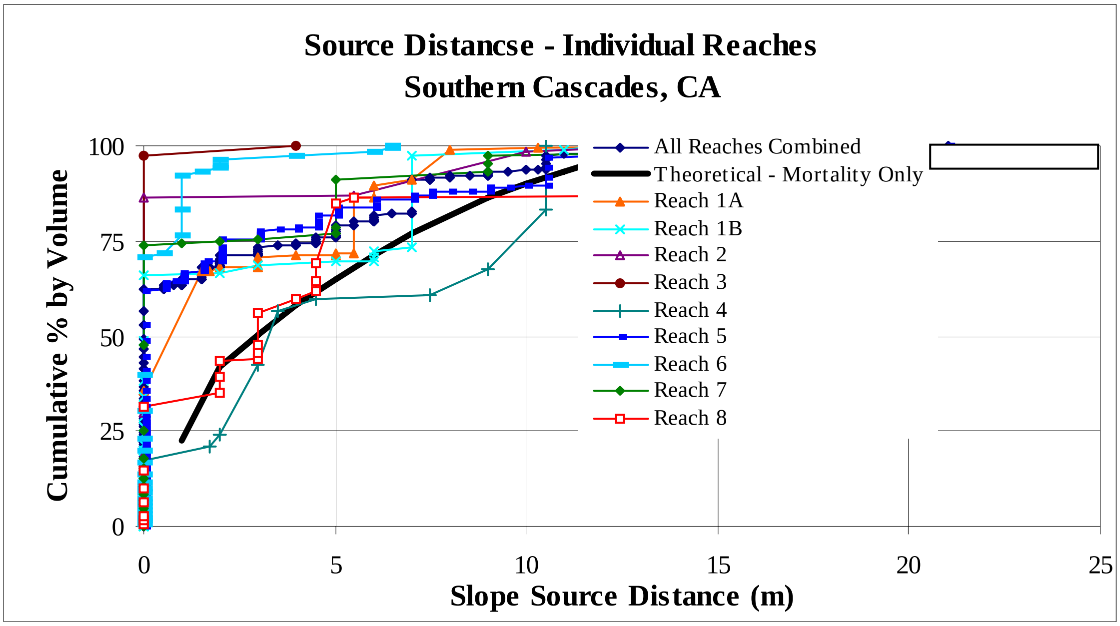


Figure 14) Variations in source distance curves based on dominant recruitment process are plotted for streams in the Sierras in northern California (Benda et al. 2005). Mortality in this figure refers to treefall.

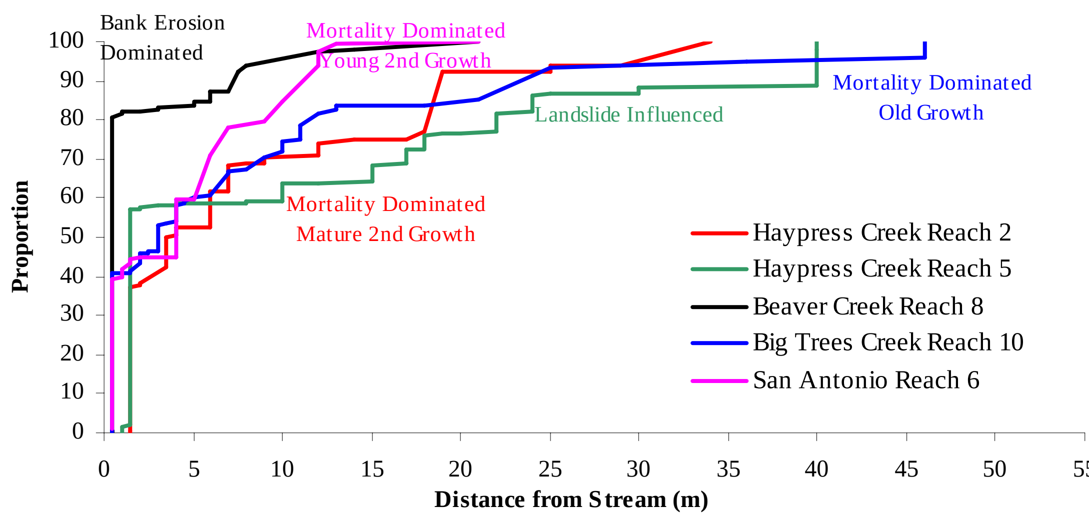
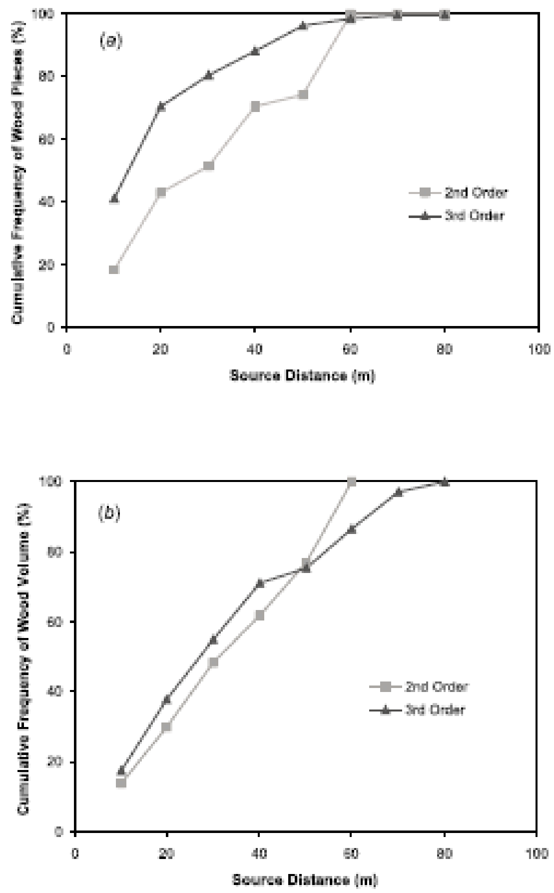
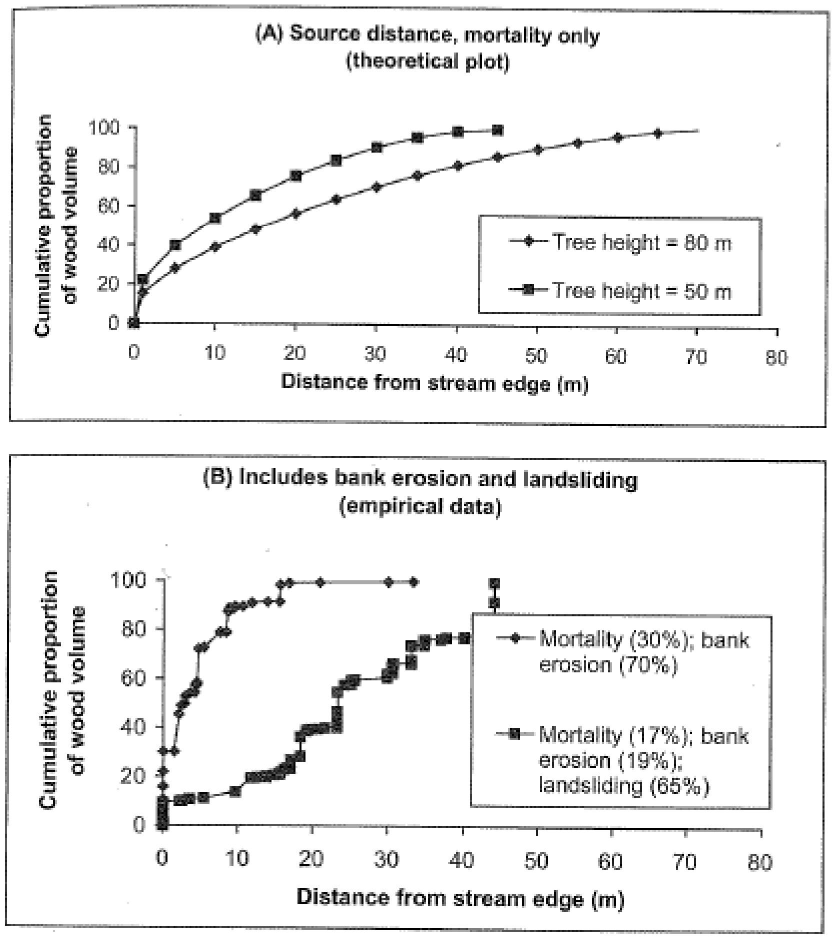


Figure 15) The source distance of large wood a) pieces and b) volume for second-order colluvial tributaries and the third-order mainstem channel in the North Fork Cherry Creek basin (May and Gresswell 2003). Mortality in this figure refers to treefall.



Much debate about these source distance curves has occurred in the literature. Over the last 20 years, a growing recognition developing is that there is not a single "right" curve for riparian recruitment, but that there are families of curves that depend on the relative proportion of wood contributed from various sources. These process variations can often be inferred from the site context (e.g. topography, confinement, stream type/order, etc), as described in more detail in Section 0.

Figure 16) Theoretical predictions of source distance for two different tree heights based on random tree fall (A). Field data demonstrating difference source distance relationships due to recruitment by bank erosion and streamside landsliding (B). NOTE: mortality in figure refers to treefall. (*From Benda et al 2003*).



- For areas that are dominated by mortality-driven treefall, about 80% of potential short-term wood recruitment typically occurs within the first 20 m (65 feet) from a channel with the remaining 20% of wood coming from the next 20 m (65 feet) of the riparian zone (Figure 17 and Table C) (Benda et al. 2002; Benda et al. 2003; Benda et al 2004; Benda et al. 2005).

- Areas prone to windthrow can dramatically shift this zone of maximum efficiency away the channel by increasing the proportion of wood that falls toward the stream (Liquori 2006). This study also found that windthrow dramatically increased the total amount of wood delivered to the stream (i.e., more trees fell toward the stream than would occur in the absence of windthrow).

- Areas prone to *streamside* landsliding shift this relationship away from the channel (Benda et al. 2002; Benda et al 2003; Benda et al. 2004; Benda et al. 2005; Martin and Benda 2001). In steep areas prone to debris flows, certain landscapes (coast and Klamath Mountains), might benefit by some retention of large trees along certain headwater streams (May and Gresswell 2003).

- Areas where bank erosion is a dominant source of wood, most wood is generated from a much narrower zone. However, where bank erosion is so pervasive as to result in significant channel migration, a much wider zone might be appropriate to accommodate the encroachment of the channel into riparian areas over time. The width of such channel migration zones depend on the specific site conditions and potential for the channel to move over time which is constrained by several processes and conditions beyond the scope of this study to describe.

We note that this approach to establishing buffer widths describes only the amount of wood that has been observed to be recruited from adjacent riparian stands. It assumes that the stocking of the riparian zone is appropriate (it may not be) and that forest management within or near this zone will not affect long-term production and recruitment processes (it can).

Figure 17) Typical zones of wood recruitment. The Streamside Bank Erosion Zone in California can typically provide 30-60% of the total observed instream wood. Up to 90% of the total observed instream wood load is usually recruited from the combined Streamside Bank Erosion Zone and the Inner Core Mortality Zone. The width associated with the Inner Core/Cuter Core transition is described in Table C. (*source: Lee Benda*).

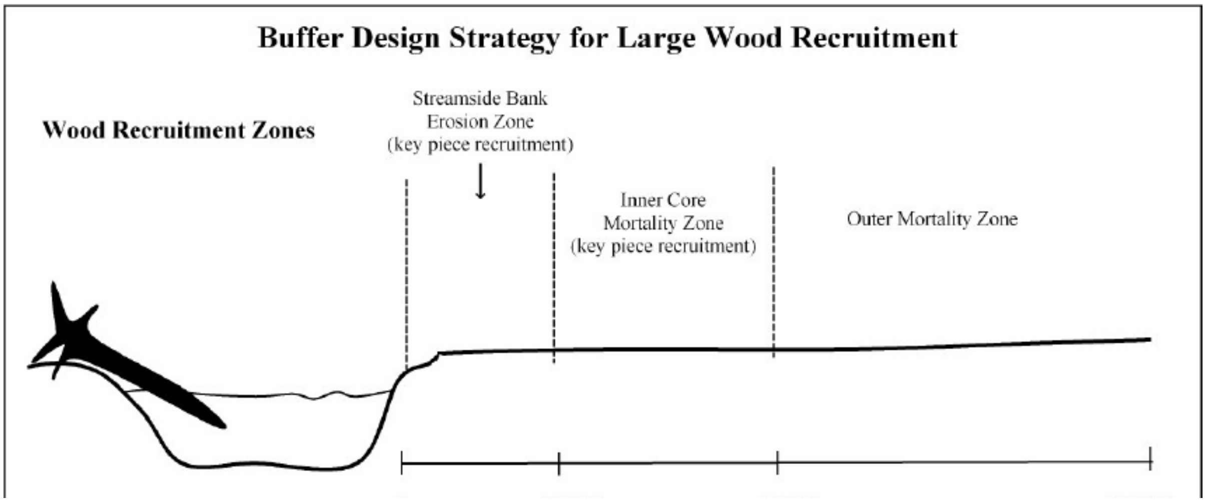


TABLE C) Typical effective source distances for California regions (based on Benda et 2003; Benda et al 2005; Reid and Hilton 1998); also see Figures 11):

Site	Observed Efficiency	Distance	Dominant Source	Notes
Mendocino County	90%	26-46 ft (8-14 m)	Bank Erosion	Includes streams affected by stream cleaning
Mendocino County	90%	115 ft (35 m)	Wind	
Redwood Region	90%	98 ft (30 m)		
Redwood Region	90%	164 ft (50 m)	Streamside Landsliding	
Southern Cascades	80%	16 ft (5 m)	Bank Erosion	
Western Sierras	70%	33 ft (10 m)		
Western Sierras	92%	66 ft (20 m)		
Klamath	80%	66 ft (20 m)		

HOW CAN FOREST MANAGEMENT PRACTICES ENCOURAGE STAND CONDITIONS THAT PRODUCE AND MAINTAIN THE POTENTIAL FOR FUTURE IN-STREAM WOOD OVER TIME?

Based on the reviewed literature, and as discussed in previous sections, wood recruitment to streams is strongly dependent on the varying importance of the different wood recruitment processes, including bank erosion, mortality, landslides, and disturbances (e.g., wildfire, infestation, disease, etc). The predominant wood recruitment processes depend upon geomorphic and ecological factors that vary spatially within individual watersheds and across physiographic regions in California. Wood loading is also dependent on the forest type (larger older redwoods supply more wood compared to smaller trees in the Sierras), structure, and the successional state of the forest (e.g., young vs. old).

The literature addresses several approaches to setting forest management goals for wood recruitment. We outline them here as it affects the response to wood loading issues.

Understanding the existing site-specific controls on wood abundance in streams can focus forest management by directing the most appropriate treatments in support of these functional processes (Liquori 2000; Lassettre and Harris 2001; Lisle 2002; Bisson; Rieman et al. 2003; Benda et al. 2003; Benda et al. 2005; Liquori 2006). As such; targets are set for each site based on their short-term and long-term potential. Process domains can be mapped with a fair degree of accuracy using existing GIS tools, aerial photos, geospatial models, and/or field criteria.

These tools could be used to establish maps or to evaluate generalized prescriptions that guide forest management. These tools might also be appropriately used in an adaptive management context to validate assumptions about forest treatments over time and space and to test site effectiveness.

Forest Management Approaches

Riparian management strategies require consideration of both science and policy. The reviewed literature offers many opinions, but little hard data to evaluate the scientific effectiveness of any approach. Ultimately, the choice of the best approach must be guided by forest policy.

Riparian Reserves

This approach seeks to maintain large buffer widths in order to minimize management effects within riparian areas, specifically those indirect management effects on natural rates of disturbance (FEMAT 1993; Spence et al. 1996; Reid and Hilton 1998). This approach typically calls for uniform and continuous riparian buffers of up to two site-potential tree heights on fish-bearing streams and one site-potential tree height on non-fish streams. The underlying basis for this strategy is that over long periods of time (typically centuries), late-seral conditions will become re-established in riparian areas, and that such conditions best represent the long-term conditions suitable for salmonids. It also ensures that natural processes dominate in controlling the structure and functions provided by riparian areas.

Some underlying assumptions inherent in this approach is that a large untreated buffers will evolve toward mature stand conditions despite any indirect effects of management on the landscape and that the best riparian stand condition suitable to salmonids are mature to late seral conditions.

Selective Management

This approach seeks to actively design the characteristics of riparian forests (e.g., size, height, species) in a way that influences future wood recruitment potential (e.g., timing of mortality, exposure to disturbance risks) and other functions. Its focus is often to maximize the benefit to riparian functions while preserving the capacity to operate on forest lands to achieve other resource objectives, including timber harvest.

The focus is on encouraging a stand composition that targets wood recruitment characteristics most suitable to the specific stream environment. This approach recognizes that the total wood volume grown onsite is strongly influenced by stand structure (e.g., density, species, age-distributions, etc), and that tree volume and diameter can be manipulated to meet management objectives. It also recognizes that wood functions vary geographically and by stream type (Bilby and Ward 1989).

This approach also acknowledges the effects on wood growth from silvicultural treatments or other forest management activities. Often, this approach integrates information from stand dynamics to encourage growth and affect rates of mortality, typically through thinning practices (Liquori 2000 Bragg et al 2000; Welty et al. 2002; others).

This approach is limited by difficulties in estimating future disturbance rates sufficient to accurately predict wood recruitment potential over time.

Proactive Enhancement:

Another approach described by the reviewed literature is the concept of proactive instream restoration and enhancement in the form of wood placement (Bragg and Kershner 1997; Bisson, Wondzell et al. 2003; others). The ability to properly design and implement restoration or enhancement projects requires knowledge of hydrology, hydraulics, geomorphology, biology and engineering practices. Instream wood placement is a practice that is continuing to evolve in many land-use settings, and the general perception is that such projects are overall a benefit to salmonids.

One challenge in evaluating the benefits of proactive enhancement is that biologically systems are inherently complex, and determining the specific benefit from wood placement or enhancement is difficult. Other biological factors associated with ocean survival, predation, inter-annual variability, and population dynamics make conclusive determinations of success difficult. In most cases, the monitoring and research elements required to answer these questions are not sufficiently developed or implemented to provide the data necessary to evaluate success (Bisson, Wondzell et al. 2003).

Environmental Goals & Targets

It is helpful for both of the above management approaches to establish environmental goals and targets that can be used to evaluate the effectiveness of riparian management practices. Science can be helpful in establishing objective target based on empirical studies of wood loading and functional instream responses to wood.

Reference Loading Targets

Reference wood loading targets are often based on comparison to "pristine" reference reaches that have been minimally impacted by management (Martin 2001; Lisle 2002; Fox and Bolton 2007; others). While such reference sites can offer some insight to pre-management conditions, it can be difficult to extrapolate these conditions to managed landscapes. As shown in Table D, empirical studies show very wide differences in wood loading conditions both across regions and within regions (Martin 2001; Lisle 2002; Fox and Bolton

2007), and thus selecting management criteria becomes an arbitrary decision that might not reflect the physical capacity of the stream to achieve such targets (Lisle 2002). Another challenge with this approach is that natural disturbance regimes have been greatly affected by a wide array of human activities (e.g., global warming, fire suppression, stream diversions, etc) that distort the perspective that historically derived reference conditions can have toward understanding future loading potential.

TABLE D) Wood volumes (m^3/ha) from pristine reference sites in California (from Lisle 2002).

		Range		
Region	**# of sites**	**Low**	**High**	**Median**
Sierras	12	2.2	100	30
Cascades	11	36	1100	300
Klamaths	9	18	1600	250
Redwood	11	200	4600	1000

Functional Loading Targets

Functional targets seek to establish wood loading levels based on the amount needed to achieve desired ecological functions. Studies using this approach focus on the wood loading required to maximize pool density or fish habitat characteristics (Montgomery and Buffington 1995; Beechie & Sibley 1997; Berg et al. 1998; Martin 2001). The scientific debate here typically revolves around identifying "how much is enough". Biologically, there has yet to be consensus established by the literature about how much is enough (Lisle 2002; Young 2001), however there are observed geomorphic trends that suggest that there are diminishing returns on wood loading beyond about 650 pieces of large woody debris per mile (~400 pcs/km) in pool-riffle channels (see Figure 5). Loading targets for other channel types depend on the geomorphic context, and are subject to some debate.

Tools for Wood Management

In addition to setting targets, there are other tools that can be used to help support wood management in forested settings.

Wood Budgets

Wood budgets support the development of testable hypotheses for riparian management. Wood budgets can provide key data that can be useful in predicting future wood recruitment potential by using an understanding of wood recruitment processes and observed rates (Benda and Sias 1998; Benda et al. 2003). Calculations are derived by using empirical relationships for various input factors based on wood supply area (e.g., bank erosion, landslides, treefall, windthrow, etc). An advantage of wood budgeting is that it can predict the potential sources of wood based on actual source availability. However, wood budgets typically represent a steady-state snapshot in time, and they are not responsive to variations in stand dynamics that strongly influence mortality processes.

Wood budgets can be useful in tracking the sources of potential wood so that specific management objectives and targets can be set. They can be limited by the need for a wide array of empirically-derived inputs that vary across the landscape and over time. Observed rates of wood recruitment from different sources vary widely, and depend on ecological and geomorphic disturbance regimes, climatic factors, stand types, the geomorphic context for each site, etc. Wood budgets tend to be backward-looking estimates of existing wood loading. They might not necessarily represent future potential, responses to management, or responses to disturbances.

Wood Recruitment Models

There are a number of wood recruitment models that have been developed, all of which have one or more weakness (Gregory et al. 2003). Wood recruitment models offer an objective tool for comparing the recruitment trajectories under existing conditions and treatment conditions. However, currently available wood recruitment models are limited in their ability to: a) accurately predict the proportional balance between various wood recruitment mechanisms (e.g., bank erosion, mortality, windthrow, etc), and b) accurately predict actual wood loading conditions into the future. Models tend to be deterministic, and are not very effective at predicting important stochastic (quasi-random) processes like floods, landslides, infestation, etc that drive these key recruitment processes.

There are also a number of input variables that models are sensitive to, and for which limited data is available. Some variables might be informed directly through onsite measurements (e.g., stand density, site index, channel width, buffer width, etc). Other factors like depletion rates (Murphy and Koski 1989; Welty et al. 2002; Gregory et al. 2003; Hassan et al. 2006), breakage (Van Sickle and Gregory 1990; Liquori 2006), and treefall direction (Bragg and Kershner 2004; Liquori 2006) can be difficult to inform locally, and might require regional databases to properly inform. Alternatively, guiding rules might be developed to minimize the reliance on these uncertain factors.

INFERENCES FOR FOREST MANAGEMENT

There is a large body of literature that examines the relative importance of the various wood recruitment processes to streams. Our review considered over 100 papers related to wood recruitment, yet it is a fraction of the information available. There are wide variations in the opinions expressed in the literature, and many of the opinions expressed are not necessarily supported by data. Studies often draw speculative or simplistic conclusions that extend beyond the data that were collected. Many studies focus on small sub-sets of issues or synthesize literature from many sources. Few papers fully integrate all the dimensions associated with wood production and recruitment in riparian forests.

There has yet to be developed a single recognized ecological endpoint for which individual streams should be managed (Young 2001), and thus effective riparian management might consider measures that provide sufficient integrity and resilience so that each riparian exchange function can persist over time (Rieman et al. 2003). Policies that establish management objectives might help to focus scientific resources to better address riparian management practices.

Despite the varied opinions expressed in the literature and the general lack of scientific consensus, there are some emerging trends in the reviewed literature, which we highlight below.

The relationship between the width of wood recruitment has been fairly extensive studied in several diverse regions in California, and is available through a database on wood recruitment specifically targeting California landscapes (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005). These studies show that there is no single relationship between buffer width and wood recruitment because the zone of maximum effectiveness varies by contributing mechanisms, and these mechanisms vary over time and space. However, 70-90% of wood is recruited within 30-100 ft (10-30 m) in most areas.

Wood recruitment processes are highly dynamic, and there are typically wide variations in the natural rates of recruitment from each process from various locations within the landscape. Specific stream sites are prone to variations in wood recruitment rates over time in response to changes in growing space and disturbance risk.

Wood recruitment processes (i.e., bank erosion, treefall, streamside landsliding) in headwater channels are not significantly different compared to larger fish-bearing streams, however the rates associated with these processes are different, and the importance of each process can vary across the landscape.

Streamside landsliding can be an important source of woody debris at certain locations in a watershed across all physiographic areas. Headwater streams can be prone to debris flows in certain physiographic areas in California and thus can be a significant source of wood to larger fish-bearing streams (primarily Coast Ranges and Klamath Mountains). Areas prone to streamside landsliding and/or debris flows can be determined using various tools (e.g., models, maps, etc) based on geomorphic and hydrologic criteria; however such tools cannot accurately predict the risk of landslide occurrence, but might be able to estimate probability of occurrence, which might support risk-management strategies. In certain landscapes, wood in debris flow deposits can play an important ecological role (Reeves et al. 2003; May and Gresswell 2003; Benda et al. 2003; Reeves et al. 2003). Although wood delivery by debris flows occurs in California, its role in supporting instream wood loading is not well understood.

These generalizations must also be considered within the context of California's diverse physiographic regions. Wood loading is responsible for many habitat features in coastal and Klamath basins but woody debris has substantially less effect on habitat in steeper boulder bedded streams that are common in the Sierras (Ruediger and Ward 1996).

While wood recruitment is important, the long-term production of healthy and resilient riparian vegetation might be locally more important in some settings than short-term wood debris amounts and inputs into riparian systems. The risk associated with these strategies can be best offset by applying spatially variable treatments across the landscape and tracking the response to such treatments in a rigorous, scientifically valid manner (Bisson, Rieman et al. 2003; Dwire and Kaufman 2003; Rieman et al 2003; others).

The most significant constraint on the recovery of riparian wood functions is the age and structure of riparian forests, which is at least partly a function of legacy forest management practices. Complete recovery of the wood exchange function might require that the distribution of riparian forests become dominated by more mature stand conditions than currently exists in California. Recovery can be improved by managing the riparian stand to affect: 1) the dynamics between growth and mortality, and 2) maintain an appropriate distribution of disturbance regimes based on the ecological context for the site. Such strategies might require a full suite of management tools.

There can be negative consequences to unmanaged riparian buffers that might be detrimental to salmonid resources. Examples include excessive wind damage in buffers adjacent to clearcuts (Lisle and Napolitano 1998; Liquori 2006); increased risk of catastrophic (stand-replacing) riparian fire risk associated with unmitigated fuel loading (Murphy et al. 2007); and delay in recovery associated with suppressed stand growth (i.e. stagnation) (Welty et al. 2002).

INFORMATION GAPS

There are several data gaps involving wood recruitment in California streams. These include:

1. Wood recruitment related to debris flows. Although this process was observed to be locally important in several regions in California (particularly the coastal and Klamath mountains), it remains unquantified. A combination of modeling and field work could resolve this outstanding question. For example, application of debris flow models to areas such as the upper Sacramento and Klamath (using NetMap, Benda et al. 2007 as commissioned by the USFS) revealed headwater streams that might have a high potential for delivery wood to fish-bearing streams by debris flow.

2. The importance of wildfire as a wood recruitment agent in California is not known. Field studies and or simulation modeling (e.g. Benda and Sias 2002) could be used to estimate the importance of wood recruitment by post fire toppling. Simulation modeling using an estimated 150 year fire rotation indicated fire related wood loading could approach 50% (Benda and Sias 2003). Longer fire rotations (250 yrs) greatly diminish this proportion (~5 to 10%).

3. Buffer designs need to predict in-stream wood production based upon current forest structure and species composition. Regional differences in wood production are documented with Northern California and the Pacific Northwest loadings higher than other parts of the West (Harmon et al. 1987; Bilby and Bisson 1998; Lassettre and Harris 2001).

4. Future life-cycle, death and decay studies are needed to depict the regional differences with various forest structures and species compositions given endemic and epidemic mortality agents such as insects and disease (species or host specific) as well as abiotic events (e.g., fire, landslides, windstorms, etc.).

5. Supply from headwaters. The supply of wood from headwater streams is not well documented for California. Studies that document the transport distance for both fluvial and debris-flow transport processes will help to establish proper longitudinal source distance lengths.

6. The effectiveness of wood placement projects as short-term enhancements or mitigation for poorly stocked riparian

sources should be evaluated. Such studies should consider the benefit to habitat development and maintenance, the fish response, and the time for which such placement projects are effective.

7. California-specific studies that evaluate the biological benefits to specific wood loading conditions to help establish instream wood targets for managed areas. Such studies might consider geomorphic response (e.g. Montgomery and Buffington 1995; Beechie and Sibley 1997), or biological response.

GLOSSARY

Debris Flow — a form of mass wasting where landslides mix with floods to create a highly destructive slurry of water, mud, rock and debris that can scour downstream for long distances

Disturbance — any of a number of physical processes that result in premature mortality or alteration of stand structures. Disturbance processes may include fire, wind, flood, landslides, debris flows, infestation, disease, animal damage, ice breakage, avalanches, etc. The level of impact from disturbance is often related to its frequency (how often it occurs) and its magnitude (how big the disturbance is).

Fluvial Transport — movement through the channel network by way of streamflow processes

Headwater Channels — small tributaries that drain hillslopes and connect to the stream channel network. Typically non-fish bearing.

Higher-Order Streams — stream order is a way to classify segments of the channel network based on the topology of the network (the number of junctions of similar segments). Higher-order streams are typically larger streams that are fish bearing. In the case of this review, typically 3^{rd}-5^{th} order streams.

Hollow — an unchannelized swale (depression) on the hillslope that is immediately upstream of the channel, and which is prone to saturation. Hollows can be sources of groundwater supply and when sufficiently steep, can be sources of landslides and debris flows

Ingrowth — trees that germinate and/or are released from the understory when sufficient canopy gaps are created either through management actions or disturbance

Landslides — a failure of a hillslope in which large portions of

	the hillslope slide downslope. Typically associated with large storms.
Larger Rivers	Typically very high-order streams (>6th order)
Legacy Effects	effects associated with past forest management practices. See Section 2.2
Mass Wasting	any of a number of hillslope processes in which large volumes of sediment move together as a single fluid (or solid) mass
Stand Dynamics	the response of tree growth and mortality conditions that corresponds to the overall stand structure. Mortality and growth are dynamically linked within the stand.
Stem Differentiation	different growth rates that occur within a stand in response to its structure, age, size distribution and species. For example, during the first 100 years or so Douglas fir trees will grow more rapidly (differentiate) compared to redwood in the same stand. During differentiation, some trees will grow in height and diameter, and others may become suppressed (demonstrating little or no growth).
Stem Exclusion	a successional phase in which competition for growing space begins to cause mortality (death) in suppressed trees.
Streamside Landslides	landslides that occur in confined valleys adjacent to streams
Succession	a series of forest structures and conditions that typically occur "in succession", following typical periods of growth and mortality. Succession concepts have given way to stand dynamic concepts

REVIEWED LITERATURE

Barrett, S.W., 1988. Fire suppression's effects on forest succession within a central Idaho wilderness. West. J. Appl. For. 3, 76–80.

Beechie, T. J. and T. H. Sibley (1997). Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. Transactions of the American Fisheries Society 126: 217-229.

Benda, L. and T. Dunne (1997b). Stochastic Forcing of Sediment Routing and Storage in Channel Networks. Water Resources Research(33): 2865-2880.

Benda, L. E. a. J. C. S. (1998). Landscape controls on wood abundance in streams. Olympia, Washington, Washington Forest Protection Association: 60.

Benda, L. E., P. Bigelow, and T.M. Worsley (2002). Recruitment of Wood to Streams in Old-Growth and Second-Growth Redwood Forests, Northern California, U.S.A. Canadian Journal of Forest Research(32): 1460-1477.

Benda, L. E. a. J. C. S. (2003). A quantitative framework for evaluating the mass balance of in-stream organic debris. Forest Ecology and Management 172: 1-16.

Benda, L. E., D. Miller, J. C. Sias, D. Martin, R. Bilby, C. Vehldhuisen, and T. Dunne (2003). Wood Recruitment Processes and Wood Budgeting. Transactions of the American Fisheries Society 37: 49-73.

Benda, L. (2003). Wood Recruitment to Streams; Cascades and Klamath Mountains, Northern California. Mt. Shasta, CA., Lee Benda and Associates, Inc.

Benda, L. (2005). Wood Recruitment to Streams in the Sierra Nevada Mountains, Northern and Central California, Lee Benda and Associates, Inc.

Benda, L. (2004). Wood Recruitment to Streams; Mendocino Coast, California, Lee Benda and Associates, Inc., Mt. Shasta, CA.

Berbach, M. W. (2001). Biological Background for Regulatory Requirements of WLPZs. Forest Vegetation Management Conference, Redding, California.

Berg, N., A. Carlson, et al. (1998). Function and dynamics of woody debris in stream reaches in the central Sierra Nevada, California. Canadian Journal of Forest Research(55): 1807-1820.

Bilby, R. E., J. Heffner, et al. (1999). Effects of Immersion in Water on Deterioration of Wood From Five Species of Trees Used for Habitat Enhancement Projects. North American Journal of Fisheries Management(19): 687-695.

Bisson, P. A., Wondzell, S.M., Reeves, G.H., and S.V. Gregory (2003). Trends in using wood to restore aquatic habitats and fish communities in western North American Rivers., American Fisheries Society: 391-406.

Bragg, D. C. and J. L. Kershner (1997). Evaluating the Long-Term Consequences of Forest Management and Stream Cleaning on Coarse Woody Debris in Small Riparian Systems of the Central Rocky Mountains. FHR Currents... Fish Habitat Relationships Technical Bulletin, USDA Forest Service. 21:9

Bragg, D. C. and J. L. Kershner (2004). Sensitivity of a Riparian Large Woody Debris Recruitment Model to the Number of Contributing Banks and Tree Fall Pattern. Western Journal of Applied Forestry 19(2): 117-122.

Bragg, D. C., J. L. Kershner, et al. (2000). Modeling large woody debris recruitment for small streams of the central Rocky Mountains. Rocky Mountain Research Station General Technical Report, U.S. Forest Service.

Camp, A., Oliver, C., Hessburg, P., Everett, R., 1997. Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. For. Ecol. Manage. 95, 63–77.

Carlson, J. Y., C. W. Andrus, et al. (1990). Woody debris, channel features, and macroinvertebrates of streams with logged and undisturbed riparian timber in northeastern Oregon, USA. Canadian Journal of Fisheries and Aquatic Sciences 47: 1103-1111.

Cederholm, C. J., R. E. Bilby, et al. (1997). Response of juvenile coho salmon and steelhead to placement of large woody debris in a coastal Washington stream. North American Journal of Fisheries Management(17): 947-963.

Culp, J. M., G. J. Scrimgeour, et al. (1996). Simulated fine woody debris accumulations in a stream increase rainbow trout fry abundance. Transactions of the American Fisheries Society 125: 472-479.

Dwire, K.A., and Kauffman, J.B. (2003) Fire and riparian ecosystems in landscapes of the western USA. Forest Ecology and Management 178: 61-74

Everett, R., Schellhaas, R., Ohlson, P., Spurbeck, D., and Keenum, D. (2003) Continuity in fire disturbance between riparian and adjacent sideslope Douglas-fir forests. Forest Ecology and Management v. 175: 31-47

Flebbe, P. A. (1999). Trout use of woody debris and habitat in Wine Spring Creek, North Carolina. Forest Ecology and Management 114: 367-375.

Fox, M., Bolton, S. (2007) A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington State. North American Journal of Fisheries Management v27:342-359

Gowan, C. and K. D. Fausch (1996) Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. Ecological Applications 6: 931-946.

Gregory, S. V., M. A. Meleason, et al. (2003) Modeling the Dynamics of Wood in Streams and Rivers. The Ecology and Management of Wood in World Rivers. K. L. B. S.V. Gregory, and A.M. Gurnell. Bethesda, Maryland, American Fisheries Society. Symposium 37:

Harvey, B. C. (1998) Influence of large woody debris on retention, immigration, and growth of coastal cutthroat trout (Oncorhynchus clarki clarki) in stream pools. Canadian Journal of Fisheries and Aquatic Sciences 55: 1902-1908.

Hassan, et. Al. (August 2005) Spatial land Temporal Dynamics of Wood in Headwater Streams of the Pacific Northwest. Journal of American Water Resources Association (JAWA).

Hennon, P. E., M. McClellan, et al. (2002) Comparing deterioration and ecosystem function of decay-resistant and decay-susceptible species of dead trees. Symposium on Ecology and Management of Dead Wood in Western Forests, Reno, Nevada.

Hyatt, T. L. and R. J. Naiman (2001) The Residence Time of Large Woody Debris in the Queets River, Washington. Ecological Applications 11(1): 191-202.

Kauffman, J.B. and Martin, R.E. (1989) Fire behavior, fuel consumption, and forest-floor changes following prescribed understory fires in Sierra Nevada mixed conifer forests. Canadian Journal of Forest Research v.19 455-462

Keller, E. A., A. MacDonald, et al. (1995) Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek, northwestern California. Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, northwest California. US Geological Survey P1-P29

Kobziar, L.N. and McBride, J.R. (2006) Wildfire burn patterns and riparian vegetation response along two northern Sierra Nevada streams. Forest Ecology and Management 222:254-265

Kushla, J.D. and Ripple, W.J. (1997) The role of terrain in a fire mosaic of a temperate coniferous forest. Forest Ecology and Management 95:97-107

Lassettre, N. S. and R. R. Harris (2001) The Geomorphic and Ecological Influence of Large Woody Debris in Streams and Rivers, University of California, Berkeley: 68.

Liquori, M.K. (2000) Riparian buffer structure and functional dynamics: considerations for riparian design. Proceedings, AWRA's 2000 summer specialty conference: riparian ecology and management in multi-land use watersheds: August 28-31, 2000, Portland, Oregon

Liquori, M. K. (2006) Post-Harvest Riparian Buffer Response: Implications for Wood Recruitment and Buffer Design. Journal of American Water Resources Association 42(1): 177-189.

Lisle, T. E. (2002) How much dead wood in stream channels is enough? Symposium on the Ecology and Management of Dead Wood in Western Forests. Reno, Nevada, USDA Forest Service: 85-93.

Lisle, T. E. and M. B. Napolitano (1998) Effects of recent logging on the main channel of North Fork Caspar Creek. Proceedings of the conference on coastal watersheds: The Caspar Creek Story. R. R. Zeimer, USDA Forest Service: 81-86.

MacDonald, L. H. and D. Coe (in press) Influence of Headwater Streams on Downstream Reaches in Forested Areas. Forest Science.

Marcus, W. A., R. A. Marston, et al. (2002) Mapping the Spatial and Temporal Distribution of Woody Debris in Streams of the Greater Yellowstone Ecosystem, USA. Geomorphology 44: 323-335.

Martin, D. and L. Benda (2001) Patterns of in-stream wood recruitment and transport at the watershed scale. Transactions of the American Fisheries Society(130): 940-958.

Martin, D. J. (2001) The Influence of Geomorphic Factors and Geographic Region on Large Woody Debris Loading and Fish Habitat in Alaska Coastal Streams. North American Journal of Fisheries Management 21: 429-440.

May, C. L. and R. E. Gresswell (2003). Large Wood Recruitment and Redistribution in Headwater Streams in the Southern Oregon Coast Range, U.S.A. Canadian Journal of Forest Research(33): 1352-1362.

McDade, M. H., F. J. Swanson, et al. (1990) Source distances for coarse woody debris entering small streams in western Oregon and Washington [USA]. Canadian Journal of Forest Research 20: 326-330.

Nakamura, F. and F. J. Swanson (2003) Dynamics of Wood in Rivers in the Context of Ecological Disturbance. The Ecology and Management of Wood in World Rivers. K. L. B. S.V. Gregory, and A.M. Gurnell. Bethesda, Maryland, American Fisheries Society. Symposium 37:279-298

Ralph, S.C., Poole, G.C., Conquest, L.L., Naiman, R.J. 1994. Stream channel morphology and woody debris in logged and unlogged basins in western

Washington. Canadian Journal of Fisheries and Aquatic Sciences 51: 37-51

Reeves, G. H., K. M. Burnett, et al. (2003) Source of Large Woody Debris in the Main Stem of a Fourth-Order Watershed in Coastal Oregon. Canadian Journal of Forest Research(33): 1363-1370.

Reid, L.M., Hilton, S.H. (1998) Buffering the Buffer. Proceedings of the conference on coastal watersheds: The Caspar Creek Story. USDA Forest Service General Technical Report PSW-GTR-168. p 71-80

Rieman, B., Lee, D., Burns, D., Gresswell, R., Young, M., Stowell, S., Rinne, J. and Howell, P. (2003) Status of native fishes in the western United States and issues for fire and fuels management. Forest Ecology and Management 178:197-211

Robison, E. G. and R. L. Beschta (1990) Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. Canadian Journal of Fisheries and Aquatic Sciences(47): 1684-1693.

Robison, E. G. and R. L. Beschta (1990) Identifying Trees in Riparian Areas that Can Provide Coarse Woody Debris to Streams. Forest Science(36): 790-801.

Roby, K.B., and Azuma, D.L. (1995) Changes in a Reach of a Northern California Stream Following Wildfire. Environmental Management v.19:591-600

Rot, B. W., R. J. Naiman, et al. (2000) Stream Channel Configuration, Landform, and Riparian Forest Structure in the Cascade Mountain, Washington. Canadian Journal of Fisheries Aquatic Sciences(57): 699-707.

Ruediger, R. and J. Ward (1996) Abundance and Function of Large Woody Debris in Central Sierra Nevada Streams. USDA Forest Service FHR Currents: Fish Habitat Relationships Technical Bulletin, USDA Forest Service.

Russell, WH and McBride, JR (2000) The relative importance of fire and watercourse proximity in determining stand composition in mixed conifer riparian forests. Forest Ecology and Management v 150: 259-265

Surfleet, C. G. and R. R. Ziemer (1996) Effects of forest harvesting on large organic debris in coastal streams. Coast Redwood Forest Ecology and Management, Arcata, California, USA.

Thomson, J. (2006) Does wood slow down sludge dragons? The interaction between riparian zones and debris flow in mountain landscapes. PNW Science Findings(86): 1-6.

Welty, J. J., T. Beechie, et al. (2002) Riparian aquatic interaction simulator (RAIS): A model of riparian forest dynamics for the generation of large woody debris and shade. Forest Ecology and Management 162(2-3): 299-318.

Wing, M. G. and A. Skaugset (2002) Relationships of Channel Characteristics, Land Ownership, and Land Use Patterns of Large Woody Debris in Western Oregon Streams. Canadian Journal of Fisheries Aquatic Sciences(59): 796-807.

Wooster, J. and S. Hilton (2004) Large Woody Debris Volumes and Accumulation Rates in Cleaned Streams in Redwood Forests in Southern Humboldt County, California. Pacific Southwest Research Station, USDA Forest Service: 14.

Young, K. (2001) A review and meta-analysis of the effects of riparian zone logging on stream ecosystems in the Pacific Northwest. Riparian Decision Tool Technical Report #4; Center for Applied Conservation Research, Forest Sciences Department, University of British Columbia. 31pp

Additional References

Acker, S.A., S. V. Gregory, G. Lienkaemper, W. A. McKeed, F. J. Swansone and S. D. Miller. 2003. Composition, complexity, and tree mortality in riparian forests in the central Western Cascades of Oregon. Forest Ecology and Management. 173, 1-3, 293-308.

Benda, L. E. and T. W. Cundy (1990). "Predicting deposition of debris flows in mountain channels." Canada Geotechnical Journal 27: 409-417.

Bigelow, P., Benda, L., Miller, D., Reeves, G., and Burnett, K. (2007) On debris flows, river networks, and the spatial structure of channel morphology. Forest Science 53(2):220-238.

Bilby, R.E., and P.A. Bisson. 1998. Functioning and distribution of large woody debris. River Ecology and Management. In: River Ecology and Management, R.J. Naiman and R.E. Bilby, eds: 324-346. Springer, New York, New York, USA.

Bilby, R.E. . 1984. Removal of woody debris may affect stream channel stability. Journal of Forestry 82(10):609-613.

Bilby, R.E., and G.E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61(5):1107-1113.

Bilby, R. E. and Ward, J. W. (1989). "Changes in characteristics and function of woody debris with increasing size of streams in western Washington." Transactions of the American Fisheries Society 118: 368-378.

Bilby, R.E., and J.W. Ward. 1991. Characteristics and function of large woody debris in streams draining old growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic

Sciences 48:2499-2508.

Bishop, D. M. and M. E. Stevens (1964). Landslides on logged areas in Southeast Alaska. Juneau, Alaska, US Forest Service Northern Forest Experiment Station.

Bisson, P.A., Rieman, B.E., Luce, C., Hessburg, P.F., Lee, D.C., Kershner, J.L., Reeves, G.H., Gresswell, R.E., 2003. Fire and aquatic ecosystems of the western USA: current knowledge and key questions. Forest Ecology and Management 178, 213-229.

Bragg, D.C., 2000. Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system. Ecology 81 (5), 1383–1394.

Braudrick, C., Grant, G. E., 2000, When do logs move in rivers. Water Resources Research, 36(2): 571-584.

Cafferata, P.H., and J.R. Munn. 2002. Hillslope monitoring program: monitoring results from 1996 through 2001. Monitoring Study Group Final Report prepared for the California State Board of Forestry and Fire Protection. Sacramento, CA. 114 p.

DeBano, L.F., Neary, D.G., 1996. Effects of fire on riparian systems. In: Fire effects on Madrean Province ecosystems: a symposium proceedings. Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO. U.S. Forest Service General Technical Report RM-289.

Dietrich, W. E., C. J. Wilson, et al. (1986). Hollows, colluvium and landslides in soil mantled landscapes. Hillslope Processes. A. D. Abrahams. Boston, Allen & Unwin. #16: 361-389.

Ellis, L.M., 2001. Short-term response of woody plants to fire in a Rio Grande riparian forest, Central New Mexico, USA. Biol. Conservat. 97, 159–170.

Erman, N.A., 1996. Status of aquatic invertebrates. In: Sierra Nevada Ecosystem Project, Final Report to Congress, vol. II, University of California, Centers for Water and Wildland Resources, Davis (Chapter 35).

FEMAT 1993. Federal Ecosystem Management Assessment Team: Chapter V Aquatic Ecosystem Assessment. 204 pp

Franklin, J. F., T. A. Spies, T.A., Van Pelt, R., Carey, A.B., Thornburgh, D.A., Berg, D.R., Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K, Chen, J. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management 155: 399-423.

Gray, A.N. and T.A. Spies. 1996. Gap size, within-gap position, and canopy structure effects on conifer seedling establishment in forest canopy gaps. J. Ecol. 84: 635- 645.

Gomi, T., R. C. Sidle, et al. (2001). "The characteristics of woody debris and sediment distribution in headwater streams, southeastern Alaska." Canadian Journal of Forest Research 31: 1386-1399.

Gomi, T. R.D. Moore, and M. Hassan. 2005. Suspended sediment dynamics in small forest streams of the Pacific Northwest. J. Amer. Water Resources Assoc. 41(4):877-898.

Goulding, M. 1980. The fishes and the forest: explorations in Amazonian natural history. University of California Press, Berkeley, 280p.

Harmon, M.E., K. Cromack Jr., and B.G. Smith. 1987. Coarse woody debris in mixed-conifer forests, Sequoia National Park, California. Canadian Journal of Forestry Research 17:1265-1272.

Hassan, M.A., M. Church, T.E. Lisle, F. Brardinoni, L. Benda, and G.E. Grant. 2005. Sediment transport and channel morphology of small, forested streams. J. Amer. Water Resources Assoc.41(4):853-876.

Hemstrom, M.A., Franklin, J.F., 1982. Fire and other disturbances of the forest in Mount Rainier National Park. Q. Res. 18, 32–51.

Keller, E.A., Valentine, D.W., Gibbs, D.R., 1997. Hydrological response of small watersheds following the Southern California painted cave fire of June 1990. Hydrol. Process. 11 (4), 401–414.

Ligon, F., A. Rich, G. Rynearson, D. Thornburgh, and W. Trush. 1999. Report of the Scientific Review Panel on California Forest Practice Rules and Salmonid Habitat. Final Report prepared for The Resources Agency of California and the National Marine Fisheries Service. Sacramento, CA. 92 p.

Liquori, M.K. 1997. Wood loading characteristics for streams in the Klickitat Tree Farm. Champion Pacific Timberlands Technical Report. 18pp

Lisle, T. 1999. Channel processes and watershed function. Pages 4-14, in: Taylor, Ross N. (ed.). Proceedings of a Workshop, Using Stream Geomorphic Characteristics as a Long-term Monitoring Tool to Assess Watershed Function, 18-19 March 1999, Humboldt State University, Arcata, California. http://www.fs.fed.us/psw/publications/lisle/lisleHSU99.pdf

Mattson W.J., Addy N.D., 1975. Phytophagous insects as regulators of forest primary production. Science 190:515-522

Matson, P.A., Boone, R., 1984. Natural disturbance and nitrogen mineralization: wave form dieback of mountain hemlock in the Oregon Cascades. Ecology 65(5):1511-1516.

Miller, D., C. Luce, et al. (2003). "Time, space, and episodicity of disturbance in streams." Forest Ecology and Management 178: 121-140.

Miller, D. J., and K. M. Burnett. 2007. Effects of forest cover, topography, and sampling extent on the measured density of shallow, translational landslides. Water Resources Research, 43,

Minshall, G.W., R.C. Petersen, K.W. Cummins, T.L. Bott, J.R. Sedell, C.E. Cushing, and R.L. Vannote. 1983. Interbiome comparison of stream ecosystem dynamics. Ecological Monographs 53:1-25.

Montgomery, D. R., J. M. Buffington, et al. (1995). "Pool spacing in forest channels." Water Resources Research 31: 1097-1105.

Montgomery, D. R. and J. M. Buffington (1997). Channel-reach morphology in mountain drainage basins. GSA Bulletin 109(5): 596-611.

Morrison, P.H., Swanson, F.J., 1990. Fire History and Pattern in a Cascade Range Landscape. Gen. Tech. Rep. PNW-GTR-254, USDA Forest Service, Portland, Oregon, 77 pp.

Murphy, M. L. and K. V. Koski (1989). "Input and depletion of woody debris in Alaska streams and implications for streamside management." North American Journal of Fisheries Management 9: 427-436.

Murphy, K. T. Rich and T. Sexton. 2007 An Assessment of Fuel Treatment Effects on Fire Behavior, Suppression Effectiveness, and Structure Ignition on the Angora Fire. USDA Forest Service. R5-TP-025. 32 p. http://www.fire.ca.gov/CDFBOFDB/PDFS/Murphy_etal_2007_USFS_FuelsTreatmentEffectivenessStudy_Tahoe.pdf

Nakamara, F., Swanson, F.J., Wondzell, S.M., 2000. Disturbance regimes and riparian systems—a disturbance-cascade perspective. Hydrol. Process 14, 2849–2860.

Naiman, R.J., Decamps, H., Pollock, M., 1993. The role of riparian corridors in maintaining regional biodiversity. Ecol. Appl. 3, 209–212.

Naiman, R.J., Bilby, R.E., Bisson, P.A., 2000. Riparian ecology and management in the Pacific coastal rain forest. BioScience 50, 996–1011.

Noss, R.F. 2000. The Redwood Forest: History, ecology, and conservation of the coast redwoods. Island Press. 339pp.

Oliver, C.D., Larson, B.C., 1996. Forest Stand Dynamics. McGraw-Hill, New York.

Olson, D.L., 2000. Fire in Riparian Zones: A Comparison of Historical Fire Occurrence in Riparian and Upslope Forests in the Blue Mountains and Southern Cascades of Oregon. M.S. Thesis, University of Washington, Seattle, WA, USA.

Owen D.F. 1980. How plants may benefit from the animals that eat them. Oikos 35,230-235.

Pettit, N.E., Naiman, R.J., 2007. Fire in the riparian zone: characteristics and ecological consequences. Ecosystems 10, 673-687.

Reeves, G.H., Benda, L.E., Burnet, K.M., Bisson, P.A., Sedell, J.R., 1995. In: Proceedings of the American Fisheries Society Symposium on a Disturbance-based Ecosystem Approach to Maintaining and Restoring Freshwater Habitats of Evolutionarily Significant units of Anadromous Salmonids in the Pacific North-west, Monterrey, CA, USA, May 1994, pp. 334-349.

Reeves, G.H., Bisson, P.A., Rieman, B.E., Benda, L.E., 2006. Postfire logging in riparian areas. Conservation Biology 20, 994-1004.

Robison, E. G., K. Mills, et al. (1999). Storm Impacts and Landslides of 1996. Salem, OR, Oregon Department of Forestry. Ziemer, R. R. (1981). The role of vegetation in the stability of forested slopes. Proceedings from the 17th International Union of Forest Research Organizations World Conference, Japan.

Spence, B.C., G.A. Lomnicky, R.M. Hughes and R. P. Novitzki. 1996. An ecosystem approach to salmonid conservation. Funded jointly by the U.S. EPA, U.S. Fish and Wildlife Service and National Marine Fisheries Service. TR-4501-96-6057. Man Tech Environmental Research Services Corp., Corvallis, OR. 356 p. http://www.nwr.noaa.gov/1habcon/habweb/habguide/ManTech/front.htm

Spies, T.A. 1997. Stand structure, function, and composition. In Creating a Forestry for the 21st Century: The Science of Ecosystem Management. Oxford University Press.

Spies, T.A., and S.P. Cline. 1988. Coarse debris in forests and plantations of coastal Oregon. Pages 5-10 in C. Maser, R.F. Tarrant, J.M. Trappe, and J.F. Franklin (eds.). From the forest to the sea: a story of fallen trees. USDA Forest Service General Technical Report PNW-GTR-229. Published in cooperation with the USDI Bureau of Land Management, Portland, Ore. 153 pp.

Spies, T.A.. and J.F. Franklin 1991. The structure of natural young, mature, and old-growth Douglas-fir forests. In L.F. Ruggiero, K.B. Aubry, A.B. Carey, and M.H. Huff (tech coords) Wildlife and Vegetation of Unmanaged Douglas-Fir

Forests. USDA, Forest Service, General Technical Report PNW-GTR-285, Portland, Oregon. Pp. 91-110.

Stone, E.C., and Vasey, R.B. 1968. Preservation of coast redwood on alluvial flats. Science 159:157-161

Swanson, F.J., and G.W. Leinkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. U.S.D.A. Forest Service general technical report PNW-69. 12 pp.

Torres, R., W. E. Dietrich, et al. (1998). "Unsaturated zone processes and the hydrologic response of a steep, unchanneled catchment." Water Resources Research 34(8): 1865-1879.

U.S. Forest Service. 2002. Landscape Dynamics and Forest Management: Educational CDROM. General Technical Report, RMRS-GTR-101CD, USDA, Rocky Mountain Research Station.

Van Sickle, J. and S. Gregory (1990). "Modeling inputs of large woody debris to streams from falling trees." Canadian Journal of Forest Research 20(October 1990): 1593-1601.

Waring, R.H. and W.H. Schlesinger. 1985. Forest Ecosystems: Concepts and Management. Academic Press, Orlando, Fl. 352 p.

Wright, H.A., and A.W. Bailey. 1982. Fire ecology: United States and southern Canada. John Wiley and Sons, Inc. New York, 501 pp.

Young, M. K. 1984. Movement and characteristics of stream-borne coarse woody debris in adjacent burned and undisturbed watersheds in Wyoming. Canadian Journal of Forest Research 24:1933-1939.