Sound Watershed Consulting
Creating Functional Water Environments

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

Chapter 7

SYNTHESIS

for

The California State Board of Forestry and Fire Protection

September 2008

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

For

The California State Board of Forestry and Fire Protection

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EXECUTIVE SUMMARY

In this chapter, we discuss concepts that will help guide the Board of Forestry toward an integrated approach to riparian management that considers all forms and functions.

We've discovered four key findings throughout our review of the literature that extend across all the exchange functions. These include:

1. Spatial context is important, as it influences functional response patterns.
2. Longitudinal controls (along the channel length) on exchange functions in addition to lateral controls (buffer width) are important in maintaining the watershed-scale ecosystem structure that maintains aquatic habitats.
3. There are dynamic interactions among and between riparian exchange functions that alter the importance of exchange functions for any particular setting.
4. While riparian zones can buffer a stream from direct management impacts, they do not protect streams from disturbances, but in fact alter the disturbance regimes in ways that can affect the functional response expressed by both short-term and long-term evolution of riparian areas.

A shift in thinking from a "protection" mindset (e.g., buffering the stream) to an "ecosystem processes" mindset is consistent with several general themes in the literature in recent years (Nakamura and Swanson 2003; Reiman et al. 2003; Young 2001). These papers suggest that it may be a more appropriate management objective to ensure that the ecosystem processes and functions are maintained to provide desired riparian (and instream) conditions in managed settings.

There are three general approaches to achieve this objective that are promoted in the reviewed literature.

Riparian Reserves utilize large buffers so that mature to late-seral stand conditions are eventually achieved.

Resource Optimization seeks to balance appropriate protections against other management objectives.

Advanced Recovery/Enhancement manages growth and disturbance risks to influence ecosystem processes that create conditions favorable to salmonids over the short- and long-term.

The scientific basis for buffer widths is described in terms of source-distance relationships that relate width to the cumulative inputs (or limits) for various functions. The shape of source-distance curves are strongly influenced by the dominant mechanisms or riparian characteristics for contributing (or preventing) the key input associated with each exchange function in that setting. Seven specific limitations in using source distance relationships are described that raise questions regarding the utility and/or effectiveness of using source distance relationships as the sole basis for riparian management.

The scientific basis for longitudinal variation describes regional, watershed, and temporal scales of influence that combine to influence the context for habitat requirements. Managing for longitudinal variation requires an understanding of how different ecosystem processes act to form and maintain habitats throughout the channel network.

The scientific basis for headwater riparian management recognizes that headwaters affect functional responses in downstream reaches. The concept of longitudinal source-distances is offered here as an analog, wherein different characteristic input distances can be measured from the confluence of the headwater tributary junction with fish-bearing reaches. Data to support such source-distance relationships for headwater areas is limited in the reviewed literature.

Riparian forest structure is fundamentally a dynamic expression of growth and disturbance. It is the combination of structural characteristics and disturbance processes that influence functional relationships between riparian areas and salmonid habitats. Management of riparian zones can affect the types of disturbances and vulnerability to disturbances that deliver functional inputs. These disturbances can be beneficial, detrimental, or both.

Our synthesis of the reviewed literature leads us to the conclusion that the importance of maintaining ecosystem functions, including those associated with disturbance, dynamics, growth, and spatial variability, point to the need for an evolutionary step in the design and application of riparian management strategies. A more holistic strategy would integrate landscape-scale concepts into local decision criteria. A wide array of analytical tools for evaluating watershed-scale processes and conditions are available, and the reviewed literature suggests that there is considerable scientific data to inform such tools.

KEY THEMES

Generally speaking, riparian zone management seeks to influence exchange functions by:

- Delivering and retaining wood, nutrients and coarse sediment in streams, and
- Preventing large perturbations in the timing and amount of heat, water and fine sediment that are delivered to streams.

The processes that are responsible for meeting these objectives are sensitive to variability at the regional scale, watershed scale, and time scales.

The previous chapters of this literature review were focused around each of five riparian exchange functions, and were generally evaluated in isolation from each other. In this chapter, we discuss some concepts that will help guide the Board of Forestry toward an integrated approach to riparian management that considers all forms and functions.

What we learned

We've discovered throughout our review of the literature four key findings that extend across all the exchange function chapters. These include:

1. Spatial context is important, as it influences functional response patterns.
2. Longitudinal controls (along the channel length) on exchange functions in addition to lateral controls (i.e., buffer width) are important in maintaining the watershed-scale ecosystem structure that maintains aquatic habitats.
3. There are dynamic interactions among and between riparian exchange functions that alter the importance of exchange functions for any particular setting.
4. While riparian zones can buffer a stream from direct management impacts, they do not protect streams from disturbances, but in fact alter the disturbance regimes in ways that can affect the functional response expressed by

both short-term and long-term evolution of riparian areas.

1) <u>Spatial context is important</u> – We observed that the answers for many of the key questions depend on where one is located both geographically and geomorphically. For example, in-stream wood is more important along the coast than the Sierras (Berg et al. 1998), and is more important in mid-order channels than in headwater channels (Nakamura and Swanson 2003). Similarly, more shade for temperature sensitivity is needed for some streams but not for others (Allen 2008). The theme of spatial and geographical variability extends across most of the key issues with each exchange function.

2) <u>Longitudinal factors</u> – Spatial variability and dynamic processes show that riparian functions are not only influenced by width but by the influence of landforms and processes that change longitudinally along the channel network. The effective width for functions depends on process, which depends on location. Riparian management by width alone ignores multidimensional factors as reported in the reviewed literature.

3) <u>Interactions among and between riparian exchange functions</u> influence both the short-term and long-term suitability of habitat for salmonids. For example, canopy openings affect heat exchange, nutrient cycling, macroinvertebrate production, soil moisture, vegetative species colonization patterns and riparian stand growth in ways that both support and potentially harm conditions that are beneficial for salmonids. Similarly, the density of standing trees in riparian areas affects the diameter growth of trees that can recruit to the stream, the rate at which trees are recruited, and the risk of disturbance from fire, infestation, flood, etc. As such, the inherent response of the forest to management-induced change is extremely complex.

4) <u>Riparian buffers affect ecosystem processes and functions.</u> There is a growing recognition that a riparian zone does not “buffer” (e.g., protect) the stream from disturbances, but in fact alters the disturbance regimes in ways that both benefit and harm salmonid habitat conditions. Riparian management can affect riparian disturbance regimes by affecting the types of disturbance, the magnitude of disturbances and the frequency of disturbances. Since disturbance regimes are one of the driving factors that influence riparian stand dynamics and succession (Oliver & Larsen 1990; Naiman et al. 1998; Franklin et al. 2002), the long-term trajectory of riparian stands can be substantially influenced not only by the direct manipulation from forest management, but by the indirect effects of forest management on natural processes. For example, recently observed fire behaviors in riparian zones, where low intensity ground fires become damaging crown fires, demonstrates how some riparian buffers can harm salmonids by exposing the stream to risks it may not have experienced under a fully natural condition. Management actions within or near riparian areas are just one of many forms of disturbance that affect the evolution of the riparian stand. As management increases risks for some ecosystem processes, it also reduces risks in others, and it is the sum of effects that controls the outcome for salmonid habitats.

Where we are going in this chapter

Riparian functions can be viewed holistically by considering their ecological context as a way to identify risks and priorities for important functions, and in the process, explain some of the variability in these exchange function processes.

We have attempted to create a framework for synthesis that considers the literature in the context of the latest concepts that stress the occurrence and ecological importance of spatial variability, diversity, and dynamics. These ecological characteristics influence the range of conditions and natural mechanisms that support salmonid ecology (e.g., disturbance processes, material inputs, diversity of conditions, managing risks, etc.).

We explore each of these themes in more detail in the sections below. We follow with a discussion of the implications for forest management that might help to outline a framework for addressing these issues within public and private forest management in California.

THE CONTEXT FOR RIPARIAN ZONES

Forest structure is fundamentally a dynamic expression of growth and disturbance (Oliver and Larsen 1990; Franklin et al. 2002). Riparian areas in particular tend to be more prone to both growth and disturbance relative to upland stands. Therefore, it is a logical extension that the conditions in riparian forests responsible for supporting salmonid habitat depend primarily on the dynamic exchange between growth and disturbance processes in riparian areas.

A shift in thinking from a “protection” mindset (e.g., buffering the stream) to an “ecosystem processes” mindset is consistent with several general themes in the literature in recent years (Nakamura and Swanson 2003; Reiman et al. 2003; Young 2001;). These papers suggest that it may be a more appropriate management objective to ensure that the ecosystem processes and functions that maintain desired riparian (and instream) conditions are encouraged to persist in managed settings.

The reviewed literature offers no clear strategy for maintaining ecosystem processes. The debate amoung scientists follows along several predominant pathways, the resolution of which is a complex ecological policy issue. The positions are generalized as follows:

The Riparian Reserve Argument: Ecological processes and functions that occur in riparian areas are so complex, so poorly understood, so long-lived, and so sensitive to management, that riparian buffers should be as wide as possible to ensure that the effects of management (which can extend some distance into the upslope riparian zone edge) are minimized. This argument is often bolstered by the perspective that the best conditions for salmonids are perceived to be late-seral or old-growth conditions, and that large buffers will allow natural recovery processes over the period of centuries to eventually restore such conditions. A broad consensus of scientific reviews considers a one-site-potential tree height sufficient to provide most riparian functions in hillslope constrained channels over time (Young 2001). As indicated by source-distance relationships (see below), 100% of the potential delivery of most functions are provided in this width (e.g, FEMAT 1993).

The Resource Optimization Argument: It is inefficient (and perhaps unfair) to require large buffers because most of the benefit for salmonids are found in the zone closest to the stream, and thus there is a point where resource values associated with timber production outweigh the benefits to salmonids. This is often justified by the economic concept of diminishing returns.

The Advanced Recovery/Enhancement Argument: Active management of riparian zones may help the recovery of desired riparian conditions by promoting growth, substantially advancing recovery of late-seral conditions, and managing risks from undesired disturbances (e.g., fires, infestation, disease, etc.). Active management can create conditions that are favorable to salmonids over the short- and long-term and provide timber harvest opportunities that can offset the costs of actively managing these areas.

The Scientific Basis for Defining Buffer Widths in Fish-Bearing Streams

The scientific basis behind riparian management has historically been driven by a focus on the width of the riparian forest necessary to sustain each of the five exchange functions. The effective width has been defined by a series of generalized functional relationships originally described in FEMAT (1993), and explored by others (Castelle and Johnson 2000; Young 2001; Benda et al. 2002; Benda et al. 2003; others). These relationships were established using "source distance" curves that relate the cumulative effectiveness of each exchange function in terms of the distance from the stream bank (Figure 1). Initial debate in the literature centered around populating these curves with data from various settings (Castelle & Johnson 2000; Young 2001; others).

More recent studies lead us to conclude that there is no single curve that represents each exchange function in all settings. Instead, for any given setting, a unique curve can be generated that represents the integration of ecosystem processes and riparian structures that exist in that setting. In other words, the shape of the curve is strongly influenced by the dominant mechanisms or riparian characteristics for contributing (or preventing) the key input associated with each exchange function in that setting.

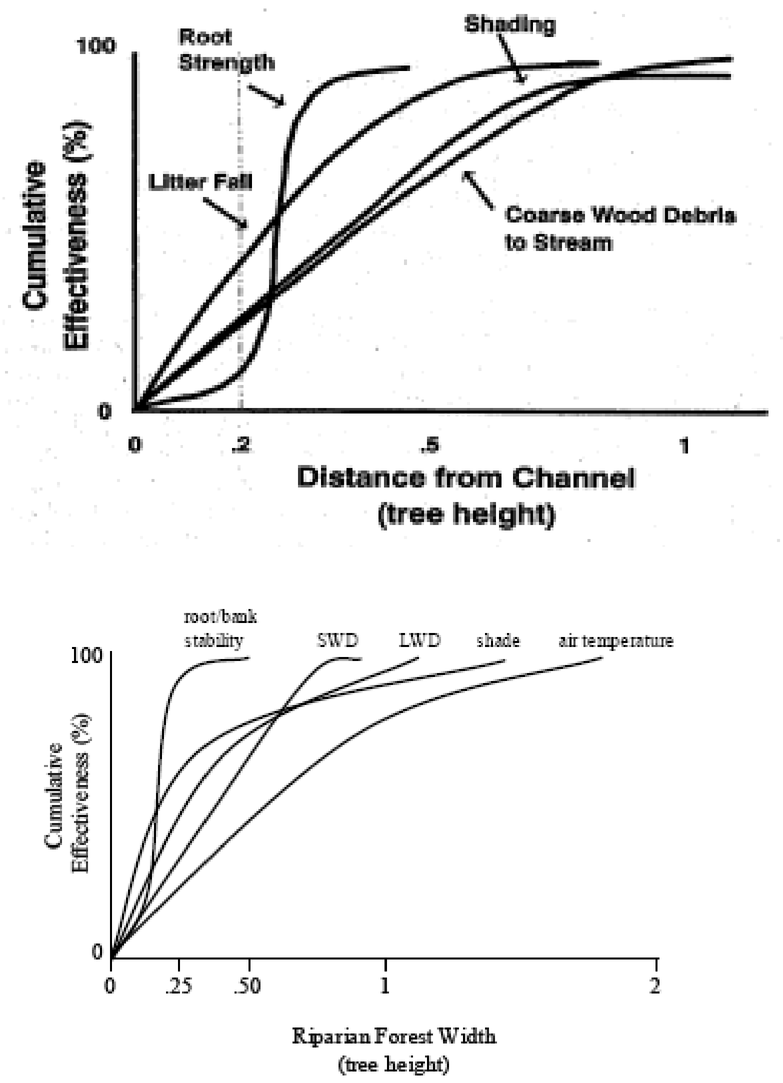

Figure 1. Examples of cumulative source distance curves A) from FEMAT (1993) and B) from Young (2001). Note the difference in the scale of the x-axis.

The source distances for wood and sediment are directly influenced by delivery processes, while the source distances for biotic and heat (and to some extent water[1]) are determined primarily by the riparian structure, which can be indirectly influenced by

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[1] *Water is a special case, because studies have not defined specific riparian effects. See Water chapter in this review.*

disturbance and growth processes. The specific variables that affect the shape of each source-distance curve include:

Wood: recruitment mechanism (bank erosion, landslide, treefall,), stand mortality (windthrow, fire, insect/disease, suppression), tree height, and valley slope/confinement;

Sediment: surface roughness, compaction, topography, soil type, geology, and local ground disturbance processes (e.g., landslides, gullies, roads, skid trails, etc.);

Heat: tree height, canopy density, topographic shading, stream orientation, and stream width;

Biotic and Nutrients: vegetative species, size, stand structure, channel morphology, and possibly valley slope/confinement.

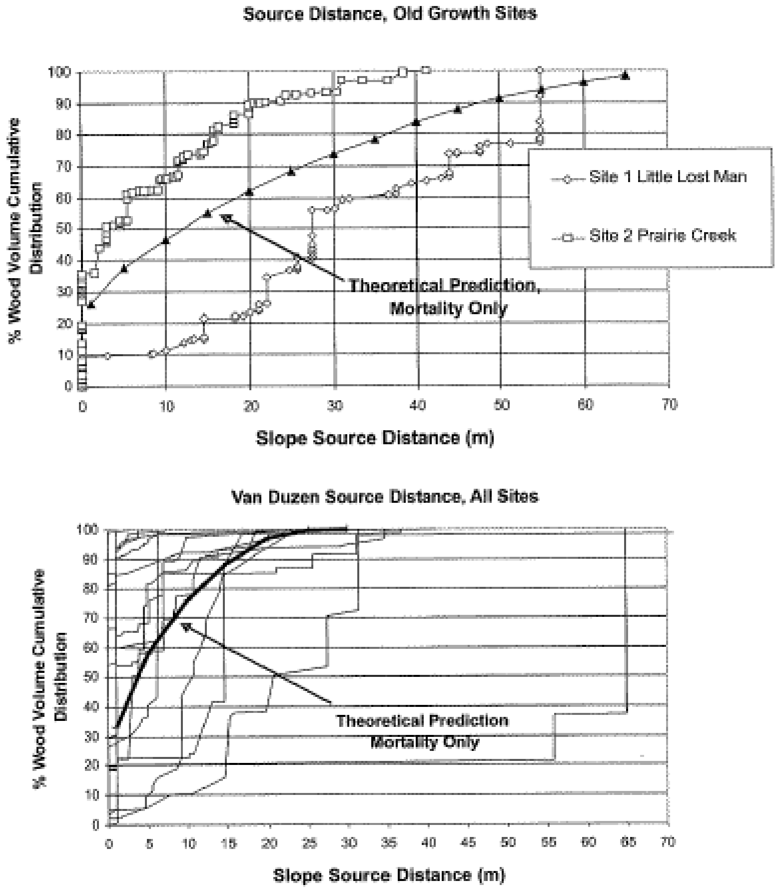

Figure 2. Source distance curves for old growth (top) and second growth (bottom) sites. In each case, the relative position of the source-distance curve can be explained by the dominant recruitment mechanism (bank erosion vs. landsliding). Note mortality in these plots refers to treefall recruitment (Benda et al. 2002).

So, for example, as described in the Wood Chapter (and Figure 2), sites that have recently experienced high rates of bank erosion express a curve that is shifted toward the stream (i.e., a greater proportion of inputs is derived from closer to the stream). Similarly, areas that recently experienced landslides or windthrow typically shift away from the stream (i.e., the source zone for wood extends further out from the stream).

The reviewed literature offers considerable data for wood source distance relationships, primarily because wood has generally required the widest source distance relative to other exchange functions, and may be the best studied (at least in the general sense – specific site conditions may vary). This data can be used to establish prescriptive relationships suitable to conditions in California.

Despite the widespread study and use of source-distance relationships, there are several limitations with using these relationships as the sole basis for setting riparian management prescriptions, such as:

The instream biological response to source distance relationships has not been established. There is little empirical information, and large degrees of variation in existing data about the biological effectiveness associated with specific riparian buffer widths (Young 2001).

Source distance relationships ignore the trade-offs between functions. In any given setting, the larger source distance may not be the limiting factor from the perspective of aquatic communities. For example, in some settings, deciduous litter inputs may be the limiting biological factor and managing to maximize wood source distance may reduce the development of deciduous understory and associated exchange functions.

Source distance relationships downplay the importance of the quality of contributed inputs. Source distance relationships describe the effectiveness of delivering (or preventing) a particular input to the stream. They do not address the quality of that input, or how the quality may be affected by the prescription.

Source distance relationships only capture the effects of some disturbances. Many of the important disturbances that are responsible for affecting supplies of wood, nutrients, and sediment occur during large events (e.g., floods, fires, etc.). While some recent studies have begun to look at disturbances associated with wind (Liquori 2006; Martin and Grotefendt 2007), landslides and bank erosion (Benda et al. 2002; Benda et al. 2003; Benda et al. 2004; Benda et al. 2005), other riparian disturbances (e.g., fire, insect/disease) are less well represented by the reviewed literature.

Source distance relationships describe the relative contribution, but not the total contribution. A higher effectiveness does not necessarily indicate a higher volume. For example, if a stream has 10 pieces of wood, and 9 result from bank erosion, then 90% of the wood comes from that process. But if a site with 50 pieces of wood has 9 from bank erosion, then only 18% comes from that process, even though the process delivered the same amount of wood. Similarly, a younger stand will typically have higher total mortality even when the rates are similar, because younger stands typically have more trees.

Source distance relationships ignore changes over time. The data used to support these curves only capture a snapshot in time. The processes that have been active during that snapshot may not reflect the long-term trends associated with that particular setting. For example, periods of fast bank erosion tend to be followed by periods of slow bank erosion. The processes that drive these mechanisms (landslides, bank erosion, wind, fire) tend to be episodic (in the case of disturbance processes) or dynamic (in the case of riparian structure).

Source distance relationships ignore the longitudinal context. Because effectiveness is defined only by the existing potential of the riparian area, it does not account for the instream needs of the site. Not all exchange functions are important in all settings. For example, in some stream types and in some geographic settings, heat risks may be less important than other exchange functions.

Across the landscape, process domains may be used to develop an integral curve that best represents the risk profile and thus the long-term average curve shape. Geomorphically-defined process domains reduce some of the variation in these curves, as certain processes can be inferred from them. For example, heat risk can be defined based on geomorphic (e.g., topographic shading) and geospatial factors (e.g., elevation, climatic zone) that can be mapped with a fair degree of confidence.

In the next section, we describe the benefit in longitudinal variation as a way to provide a mix of riparian conditions so that some exchange functions are not compromised by the effort to support another function.

The Scientific Basis for Longitudinal Variation

One of the legacies of the source-distance relationship is that the debate about impacts from forest management has primarily focused around buffer strip width. This has lead to prescriptive strategies that tend to ignore the site's context within the channel network, at least in the absence of more detailed and costly analytical study (e.g., watershed analysis).

The science community has long recognized that longitudinal variations are an important ecological component of natural environments (Naiman and Bilby 1998). Variation occurs in nature in response to differences in geomorphic and geographic context that control the magnitude, frequency and intensity of natural disturbance processes. Since forest management imposes its own characteristic disturbance signature, it is reasonable to consider that variation in management might lead to greater diversity, richness and reduced risk.

Regional variability is expressed in the different ways that salmonid habitats are established and maintained. For example, Coast Range habitats are driven by wood and sediment loading that are predominantly influenced by landslides, flooding disturbances, and in some locations wind. By contrast, the Sierra's appear less responsive to wood and sediment loading, and more strongly influenced by fire disturbances.

Watershed variability is expressed in the different risks, rates and characteristics of ecological processes and their distribution across the landscape. Small headwater streams are influenced by different sets of processes, functional inputs, and habitat requirements than are larger rivers.

Time variability establishes the trajectory of recovery processes, the timing and frequency of disturbances, and the extent of risk in riparian forests. Time also influences the changing distribution of habitat types across the landscape as systems respond to ecological, geomorphic and biological processes.

In order to effectively outline general trends for any exchange function, it's important to understand these scales of variability. For example, there are forms of regional, watershed and temporal variability in ambient air temperature, vegetation type, sediment sources and characteristics, controls on topographic shading, stand growth and mortality dynamics, biological productivity, and hydrological process.

Debates remain as to how to implement variations across the landscape in a way that doesn't compromise salmonids. This section describes some common themes of longitudinal variation that are widely held within the scientific literature, and which may be captured by management strategies (Figure 3).

Variability is expressed throughout the channel network in several ways:

River Continuum – One of the fundamental concepts in aquatic ecology is that there are generalized trends in functional processes and representative biota that occur as one moves downstream along the channel network (Vannote et al. 1980). For example, dominant aquatic invertebrate types change from shredders in the headwater streams to grazers in larger mainstem channels. These biological variations exist primarily in response to different ecological processes domains that influence patterns of stream energy inputs (i.e., heteotrophic and autotrophic production) along the river continuum.

Geomorphic Context – Different landscape conditions contribute to differences in the stream environment. Such differences influence the dominant instream processes that are affected by inputs from riparian functions. The geomorphic context can be described by various stream classification systems (Rosgen 1994; Montgomery and Buffington 1997) that generalize stream conditions based on channel gradient, confinement, sediment supply, etc. Inherent in these systems is a recognition that different processes contribute to the organization of the stream and its suitability to various aquatic communities.

Biological Hotspots – There are certain landscape features that can offer rich and diverse habitat conditions where salmonids and other aquatic communities can thrive. Such features include floodplains, confluence zones, alluvial fans, side channels, off-channel habitats, etc. The locations, distribution, and size of these features are generally predictable as they are a result of interactions among landforms and geomorphic processes.

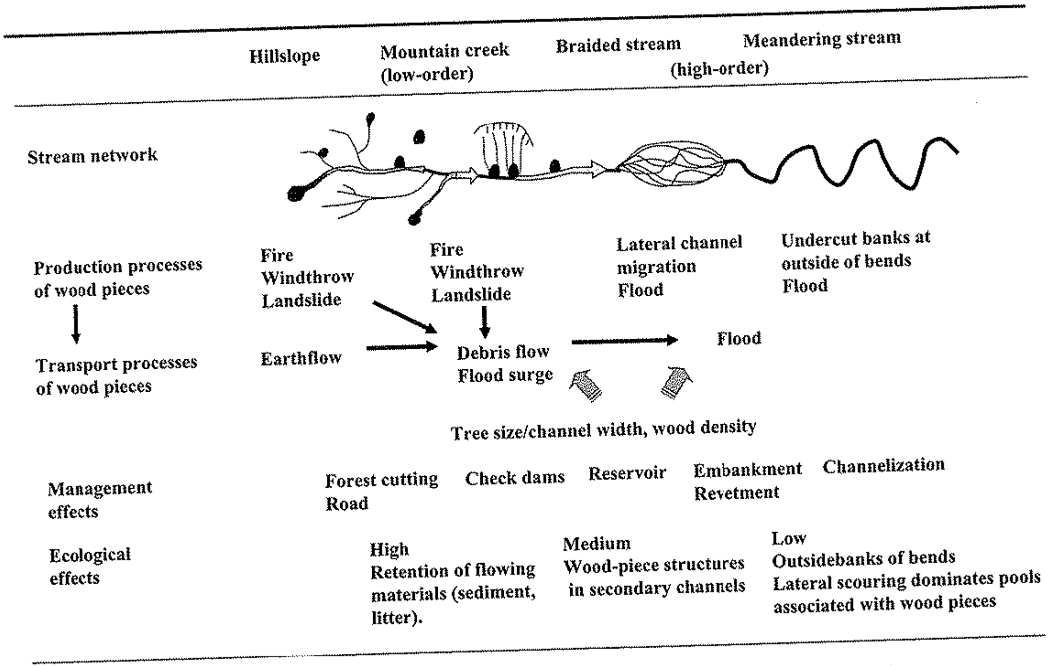

FIGURE 10. A framework for applying results in different geographic and management settings.

Figure 3: A framework for applying results in different geographic and management settings (Nakamura and Swanson 2003).

Recent perspectives of aquatic ecosystems are also focusing on spatial heterogeneity of habitat forming processes and associated physical habitat features at the scale of feet to miles, driven by alternating canyons and floodplains, tributary confluences, landslides, and log jams etc. (e.g., Montgomery 1999, Nakamura and Swanson 2003). The perspective of patchy habitat formation and its related variability driven by landscape disturbances and inherent spatial variability of landscapes and stream systems has influenced much current thinking in riverine ecology (e.g., Bisson et al. 2003; Benda et al. 2004).

The Scientific Basis for Headwater Riparian Management

Headwater streams comprise the majority of the stream network, in some landscapes as much as 80% of the entire channel length. This extensive distribution of channels creates a high edge to area ratio for small streams that result in tight coupling of the riparian functions to the aquatic environment (Richardson et al. 2005).

The general concept of source distances or influence zones applies to headwater riparian management, just as it does for fish-bearing reaches. However, the importance of riparian inputs in headwater systems depends on two factors:

- **Local requirements** – what does the headwater stream itself require to support aquatic organisms and what are the resource management goals for these streams, and

- **Downstream inputs** – what inputs are important to support downstream fish-bearing reaches?

There is very little information to inform the first topic in the reviewed literature. Therefore, our discussion is focused on the downstream importance of headwater stream functions and the length of headwater buffers, or influence zone that affects export materials from headwater streams.

Longitudinally, the buffer length should be sufficient to limit certain key inputs (heat, sediment, water), while promoting others (invertebrates, smaller wood, organic litter). Downstream transport of material inputs is more relevant for some functions than for others. As in the fish-bearing streams, the width of the headwater buffer might benefit by understanding the specific objectives relevant to the site. For example, wood inputs appear less relevant than limiting sediment inputs in headwater streams that are fluvially controlled (MacDonald et al. 2004), but wood may be more relevant in streams where debris-flow processes influence long-term processes (May and Gresswell 2003; Reeves et al. 2003).

There are different longitudinal source distances for systems dominated by fluvial transport versus debris-flow transport. The distribution of debris-flow risks can be determined based on geomorphic criteria.

Similar to lateral (width-based) source-distance relationships, we envision that there are longitudinal source-distance relationships that are relevant to headwater functions. To our knowledge, these have not yet been developed, however, we have some indication of the relative scale for given inputs. These were discussed in more detail in the exchange function chapters, but general examples include the following:

- Sediment transport distances tend to vary depending on the size of material delivered to the stream. Fine sediment typically has transport distances from headwater areas that are relevant at a scale of about 30,000 feet, sand transport is relevant at about 6000 feet, and coarse sediment is relevant at about 300 feet (NCASI 1999). These distances can be influenced by the volume of instream debris, the type of stream, and valley gradient, among other factors. Sediment sources can come from instream erosion (Lewis et al. 2001), roads (Megahan and Ketchison 1996), and upslope erosion (Rashin et al. 2006).

- Wood transport distance from headwater streams is typically short (< 200 m) in fluvially dominated landscapes (Benda et al. 2005; Martin & Benda 2001). Also, the majority of fluvially transported LWD pieces are smaller than the channel width (Martin and Benda 2001, May and Gresswell 2003). In debris-flow dominated landscapes, the instream wood loading tends to be concentrated near confluences and channel gradient transitions where sediment and wood from debris flows are deposited (Benda et al. 2003; others).

- Invertebrate production is strongly influenced by local riparian conditions (Romero et al, 2005) and insect drift distance is less than 100 m (300 ft) during low-flow conditions (Danehy unpublished MS). Therefore most of the invertebrates delivered to larger streams originate in close proximity to the headwater stream junction. Similarly, coarse litter (leaves and twigs) is processed locally and fine particulate is transported out of headwaters.

- As discussed in the heat chapter, we know that downstream temperature influence is typically mitigated in 500 to 650 feet (150-200 m) (Caldwell et al. 1991).

To summarize, fine sediment and fine litter may be derived from along the entire headwater channel. But wood, coarse sediment, coarse litter, invertebrates are primarily derived from within several hundred feet of tributary junctions. Management of the adjacent headwaters can influence habitat and aquatic production immediately downstream. Thus, it appears that headwater streams might benefit by focusing on the following functional objectives:

- supporting inputs for nutrients, invertebrates, litter and small wood;

- limiting inputs of fine sediment and, where relevant, heat;

- considering the role of canopy interception in regulating storm effects in colluvial hollows (zero-order channels)[2]; and,

- supporting functions important in biological hotspots (e.g., tributary confluences, alluvial fans) (Benda et al. 2004).

It may be reasonable to note that discontinuous buffers may provide sufficient protection for headwater systems.

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[2] *There was very little relevant discussion addressing these issues in the reviewed literature.*

THE INFLUENCE OF MANAGEMENT ON DISTURBANCE AND DYNAMIC PROCESSES

We've established that the riparian structures and landforms influence source distance relationships and the inputs provided by exchange functions. Riparian structure and growth conditions are particularly responsive to two classes of ecological processes:

Disturbance –We define disturbance broadly as those processes that physically alter the structure of the riparian community, or otherwise cause premature stand mortality. They include fire, wind, ice-breakage, flooding, erosion, landslides, debris flows, avalanches, insect and disease infestations, animal damage, harvest activities, etc.

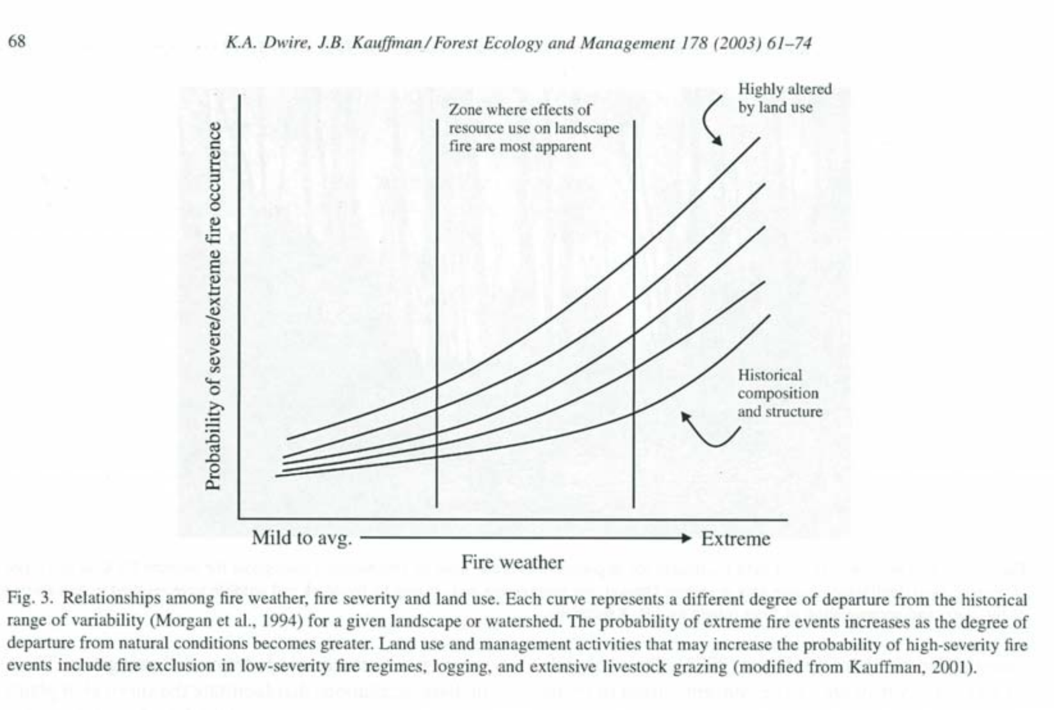
Dynamic Processes – These are systems of two or more functional processes and/or disturbance processes that interact in ways that are either self-reinforcing or self-limiting. For example, substantial coarse sediment inputs to streams can increase rates of bank erosion, which can recruit more wood to the streams, which can further increase rates of bank erosion. Similarly, wood acts to store and sort coarse sediment in ways that form complex salmonid habitats.

There is increasing recognition that disturbances and dynamic functional processes act in combination to create and maintain certain attributes of aquatic condition over time (e.g., Benda and Dunne 1997, Benda et al. 1998; others).

The Role of Disturbance Dynamics

Management of riparian buffers (or lack thereof) influences vulnerability to natural disturbance. The location and intensity of management may influence the type and potential distribution of disturbances.

In natural forests unimpacted by management, risks of disturbance are influenced by landforms, climate, and the spatial distribution of forests. Therefore, stand patterns tend to reflect the frequency, magnitude and distribution of disturbance. Management causes a shift in the distribution of these disturbance processes that may increase the risk (vulnerability) in some settings (Figure 4). In so doing, management (or lack thereof) can modify the local disturbance regime in such a way that the normal type and distribution of disturbances is altered.



68 K.A. Dwire, J.B. Kauffman / Forest Ecology and Management 178 (2003) 61–74

Fig. 3. Relationships among fire weather, fire severity and land use. Each curve represents a different degree of departure from the historical range of variability (Morgan et al., 1994) for a given landscape or watershed. The probability of extreme fire events increases as the degree of departure from natural conditions becomes greater. Land use and management activities that may increase the probability of high-severity fire events include fire exclusion in low-severity fire regimes, logging, and extensive livestock grazing (modified from Kauffman, 2001).

Figure 4) Conceptual depiction of fire risk response to landscape-scale management regimes (*from Dwire and Kauffman 2003*).

Strategies that “protect” sites from disturbance may alter the type, frequency and magnitude of disturbance, and can create conditions over time that lead to markedly different riparian structures and thus different rates of delivery for various functions (Dwire and Kauffman 2003; Liquori 2006; Martin and Grotefendt 2007). This is one of the reasons that thinking has shifted from “protecting streams” to maintaining functional processes. For example:

- Fire suppression in uplands combined with increased fuel loading in riparian areas may increase the occurrence of crown fires in riparian zones, causing preferentially more disturbance in riparian areas. This pattern has been observed in several recent California fires (e.g., Angora, Trabing, Antelope fires).

- Risks of windthrow are increased when edges are exposed along riparian zone margins, where trees have not previously been exposed to wind stresses (Liquori 2006; Lisle and Napolitano 1998; Martin and Grotefendt 2007).

- The magnitude and frequency of streamside landslides have been altered by legacy forest management practices in ways that alter the expected future frequency of streamside disturbance (Benda and Dunne 1997).

Size distributions of trees in unmanaged coniferous forests are strongly related to disturbance history and the timing and frequency of disturbance (Oliver and Larson 1990). Typical patterns of size distribution can be identified, although many stands will deviate from idealized patterns. In centuries-old, late successional forests, tree inventory information often indicates that multiple disturbance events are responsible for the stand's development (Franklin et al. 2002). Low to intermediate disturbances such as partial fires can remove understory and overstory trees, altering horizontal and spatial pattern of canopy foliage, and may be a key long-term structural component supporting aquatic communities (Agee 1993; Bisson et al. 2003).

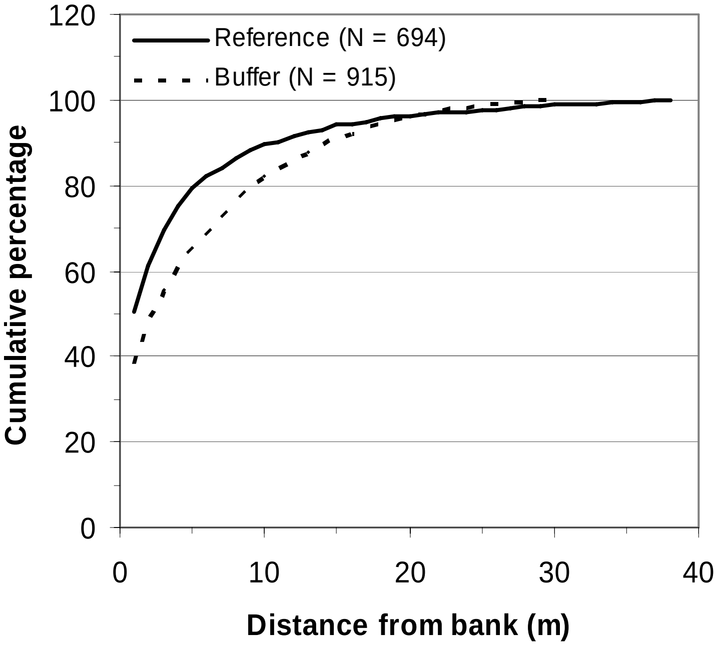


Figure 5) Cumulative distribution of source distances for downed trees in buffered and reference streams. The shift in source distance can be attributed to changes in disturbance dynamics in buffers relative to reference sites (in this case, wind). (*from Martin and Grotefendt 2007*).

One of the growing observations is that not only do disturbances affect riparian zones, but that riparian management can influence the characteristics of disturbances that occur in the landscape (Figure 5). For example, the retention of buffers in wind disturbance landscapes causes an increase in mortality within the buffer (both frequency and magnitude) that exceeds natural background (Martin and Grotefendt 2007; Liquori 2006). We can generally classify two end-members along a continuum of disturbance process dynamics:

Primarily Natural Disturbance Processes: Certain disturbance processes occur without regard to forest condition. Factors such as landsliding, bank erosion, flooding, wind and channel migration can occur primarily in response to natural processes, although in some cases they may be somewhat influenced by management. The geographic domain in which these processes are dominant can be predicted with a reasonable degree of accuracy (Montgomery 1999). For example, it is possible to identify areas prone to landsliding based on various factors (soil type, topography, geomorphic expression, hydrologic regime, etc.). Similar mapping capabilities exist for channel migration, flood prone areas, thermal loading, and wind prone areas.

Primarily Management-Influenced Disturbance Processes: Other processes can be strongly influenced by management activities, even if they are initiated by natural events. For example, fire risk is widely accepted to be a function of fuel loading, structure, and spatial arrangement of the forest (Agee 1993). Similar conditions can exist with infestation and to some extent wind. Thus vulnerability to such disturbance processes can be influenced by forest management (i.e., timing, location, and configuration of harvest units), and the relative vulnerability is also predictable over time and space, given the distribution of stand and landscape characteristics.

Disturbance processes often operate at time scales of decades, and can thus be affected not only by current management practices, but also by legacy practices.

MANAGING FOR ECOSYSTEM PROCESSES

There are a growing number of opinions expressed in the literature that suggest that managing for ecosystem processes may be the key to effective riparian management (Young 2001; Bisson et al. 2003; Nakamura and Swanson 2003; Reiman et al. 2003; others). These papers tend to argue for management strategies that are developed at watershed or landscape scales, yet specific guidance tends to be limited about how to relate such strategies back to the site scale, where management decisions are ultimately implemented.

We discovered during our literature review that while the science has advanced in many areas, our improved knowledge has potentially added complexity to management. However, landscape-level complexity and spatial variation should be one of the strategies of riparian management.

Policy should define goals and objectives for riparian strategy. However, it can be difficult for policies to explicitly define the specific tools and methods for implementing strategies, especially when the details of implementation can be so complex. Some fundamental policy alternatives are:

1. Apply the Riparian Reserve concept (at the risk of reduced economic efficiency), or

2. Define a relatively large array of prescriptions that are targeted to specific landscape conditions (at the risk of having some conditions that may be difficult to classify), or

3. Simplify the prescriptions (at the risk simplifying riparian conditions, and reducing landscape complexity in a manner that may not meet important functions), or

4. Codify the science into regulatory prescriptions (at the risk of creating a logistical nightmare), or

5. Develop a series of objective, collaborative, science-based, decision support tools that can be expressed to managers in the form of user-friendly maps, models, equations, monographs, etc. (at the risk of asking scientists to accept some responsibility for developing management tools).

Our synthesis of the reviewed literature leads us to the conclusion that the importance of maintaining ecosystem functions, including those associated with disturbance, dynamics, growth, and spatial variability, point to the need for an evolutionary step in the design and application of riparian management strategies. A more holistic strategy would integrate landscape-scale concepts into local decision criteria. A wide array of analytical tools for evaluating watershed-scale processes and conditions are available, and the reviewed literature suggests that there is considerable scientific data to inform such tools.

We suggest that it is possible, given the advances in our understanding of riparian functions, to develop objective, science-based, decision support tools. Such tools can provide sufficient spatial context for local management that targets the right riparian functions to the right landscape condition. Such tools could be informed by a framework that:

a) Establishes objective science-based criteria for determining specific, site-based input objectives that are consistent with the specific landscape context, and

b) Understands that there are landscape-scale controls that can broadly define disturbance regimes and dynamic processes regimes that contribute to (or retard) riparian structure, growth, and functional response, and

c) Recognizes patterns in the growth trajectory of stands and how management might affect the processes responsible for stem distributions (diameter, height, species and density) and mortality processes that naturally regulate exchange functions, and

d) Addresses risks at larger spatial and temporal scales, and

e) Is informed by a collaborative, applied scientific support infrastructure, including the capacity for research, monitoring, and adaptive management.

We believe that these components would form a nexus that integrates all five exchange functions in virtually every relevant landscape in California in a way that is spatially diverse and ecologically sound.

Over time, this approach would result in a greater understanding of the effects of forest management on aquatic ecosystems, including salmonids and other sensitive species. It would reduce the risk of further salmonid habitat declines, and should promote opportunities for recovery. It would provide an infrastructure for translating science into applied management tools that could dramatically simplify the permit application process. It could help support jobs in many of the rural economies of California, and it could spread the effort for species protection among agencies, private companies, consultants and academics.

KEY LITERATURE GAPS

- **Longitudinal Source Distance Relationships** – Very limited information is available on the relative source distances appropriate in the various regions in California. Empirical studies that help to develop these relationships will help calibrate local source-distance curves, and can support management.

- **Dynamic Processes in Fish-Bearing Channels** – There are known trade-offs that exist in the various inputs from riparian management. For example, concerns over long-term wood loading is often preferred over nutrient support, although there is growing evidence that nutrient support could provide more short-term benefits for salmonids. Developing better strategies for assigning these relative values and trade-offs in a way that reduces risks would greatly improve riparian management practices.

- **Dynamic Processes in Headwater Channels** – Dynamic processes in headwater streams are not well understood. For example, trade-offs between heat and nutrients, dynamics between water availability and habitat response, etc. Understanding these processes would support a stronger scientific basis for headwater riparian management.

- **Biological Response to Buffers** – Very little information is available about the biological response to riparian management. Much of the discussion of source-distance relationships is predicated on the assumption that in the inputs are provided, fish will benefit. More empirical support for this assumption would help improve management practices, and validate the state of the science. In headwater streams, the biological dependence on these riparian exchange functions to support local communities (e.g., amphibians, macroinvertebrates, etc.) has not been well established.

GLOSSARY

Autotrophic	Literally, self-feeding. Refers to organisms that obtain energy from sunlight or inorganic compounds or elements, such as nitrate, sulfide or reduced iron
Dynamic	Processes that change in response to other process or inputs
Heterotrophic	Literally, other-feeding. Refers to organisms that obtain energy from reduced carbon (dead or living plant or animal tissue)
Source distance	The lateral distance from the stream bank that supplies functional inputs. Source-distance curves typically compare the horizontal distance to the cumulative inputs provided to the stream between the bank and the reported distance.
Site-Potential Tree Height	A statistically-derived height that dominant trees can expect to achieve for a given site condition

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