A Review and Meta-Analysis of the Effects of Riparian Zone Logging on Stream Ecosystems in the Pacific Northwest

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EXECUTIVE SUMMARY

This report summarizes the results of nearly half a century of research on the effects of riparian zone logging on stream ecosystems in the Pacific Northwest of North America. After outlining the contemporary consensus on aquatic ecosystem management, I provide brief summaries of: (1) the effects of riparian logging on different physical and biological components of stream ecosystems, and (2) the functional relationship between riparian forest width (i.e. buffer width) and physical components of stream ecosystems. I then present a meta-analysis of thirty-four studies that have directly measured the effects of riparian logging on one or more of four physical and three biological components of stream ecosystems: water temperature, fine sediment load, large woody debris (LWD) load, habitat complexity, primary productivity, macroinvertebrate abundance/production, and fish abundance/production. Together, the summaries and meta-analysis suggest two conclusions. First, we have developed an empirically based and conceptually sound model for predicting the response of stream ecosystems to riparian zone logging. Second, there is substantial variation in the response of different physical and biological components of stream ecosystems to riparian zone logging. Departures from the general model are likely due to variation in channel geomorpholgy, and natural disturbance histories at both the stream and watershed scale. I suggest that the data support two key insights of the contemporary consensus on aquatic ecosystem management. **First, because of their physical and biological connectivity, stream ecosystems should be managed at the watershed scale. Second, there is no single "ecological endpoint" for which individual streams can or should be managed. Accordingly, riparian zone management strategies, and associated monitoring efforts, should be implemented at the watershed scale. Ecologically sustainable riparian zone management will require protecting watershed integrity by ensuring that water, sediment, and organic debris continue to be introduced and transported through channel networks at spatial scales and temporal rates similar to those observed in unmanaged watersheds.**

1. TERMS OF REFERENCE

In the spring of 2000, the Timber, Fish, Wildlife, Biodiversity Task Group of the Central Coast LRMP (CCLRMP) concluded that the Forest Practices Code guidelines were inadequate to protect the riparian values of the Central Coast of British Columbia. Thus, they developed a proposal for a different approach to address the key issue of riparian management in the CCLRMP.

As a result of a November 16-17, 2000 CCLRMP Biodiversity Wildlife Riparian Timber Task Group meeting in Richmond, it was agreed that a Joint Solutions Project (JSP) would be formed to provide information to help decision making on riparian issues.

I have been commissioned by the JSP to prepare a report reviewing existing knowledge of the effects of riparian zone logging on stream ecosystems in the Pacific Northwest. This report is one of several background documents prepared to aid in the development of a “Riparian Decision Tool”. The Riparian Decision Tool will help guide ecosystem based riparian zone management in the central coast of British Columbia.

2. INTRODUCTION

Scientists have studied the effects of riparian zone timber harvest on stream ecosystems in the Pacific Northwest ecoregion (PNW) (Figure 1) for nearly half a century (Chapman 1962). Early research focussed on the short term effects of logging on water temperature and fine sediment loads (Bisson et al. 1992). As data accumulated, new hypotheses were developed and tested, perspectives broadened, and our understanding of forest-aquatic interactions matured alongside relevant conceptual advances in ecosystem theory (Sousa 1984; Chapin et al. 1996). In recent years a two-part consensus has emerged regarding the effects of forestry in general, and riparian logging in particular, on lotic ecosystems in the PNW. First, channel networks are hierarchically connected physically and biologically, and the effects of forest harvest on lotic ecosystems are manifested at the watershed to basin scale over years to centuries (Vannote et al. 1980; Frissell et al. 1986; Naiman 1992; Swanson and Franklin 1992; Williams and Williams 1997; Naiman et al. 2000). Second, different physical and biological components of stream ecosystems respond to riparian logging differently through time depending on geology, climate, natural disturbance history, channel size and gradient, and community composition (Gregory et al. 1987; Niemi et al. 1990; Poff and Ward 1990).

This dual consensus provides the basis of a conceptual framework for aquatic conservation in the PNW- *watershed management*- that stresses two features of sustainable ecosystem management (Christensen et al. 1996). (1) Sustainable management of aquatic ecosystems requires a watershed-based approach that aims to protect ecosystem structure and function by maintaining natural disturbance regimes and ensuring different areas of the channel network remain in a condition that allows them to respond naturally to disturbance events over all ecologically relevant spatial and temporal scales. (2) In the absence of anthropogenic disturbance, streams are dynamic systems whose physical and biological characteristics change through time in response to natural disturbance events; there are no "good" or "bad" streams, no single ecological "endpoint" for which individual streams can be managed. This does **not** mean there are not good and bad approaches to riparian zone management. A good riparian zone management strategy is one which maintains over all ecologically relevant spatiotemporal scales the range of physical and biological conditions observed in unmanaged watersheds (Naiman et al. 1992, 2000; Bisson et al. 1992; FEMAT 1993; Sedell et al. 1990, 1994; Reeves et al. 1995; Montgomery et al. 1995; Swanson et al. 1998).

That lotic ecosystems should be managed at the watershed scale is logical. As long as water, sediment, and organic debris are subject to gravity, channel networks will be physically and biologically connected. Over a range of temporal scales, the physical and biological characteristics of higher order (larger) channels depend on hillslope and channel conditions/processes higher in the watershed. How different physical and biological components of stream ecosystems respond through time following riparian logging is less clear. Furthermore, there are few empirical data that directly address one of the most contentious issues in forestry management in the PNW: what width of riparian no-harvest zones are required to protect watersheds from the effects of timber harvest? This report attempts to shed light on these two issues by conducting a meta-analysis of 34 studies that have directly measured the effect of riparian logging on seven commonly reported physical and biological components of stream ecosystems: water temperature, fine sediment load, large woody debris (LWD) load, habitat complexity, primary productivity, macroinvertebrate abundance/production, and fish abundance/production. First, I provide two generalized graphical summaries: one of the effects of riparian logging on stream ecosystems, the other of the functional relationship between riparian forest width and various physical components of stream ecosystems.

3. ECOSYSTEM RESPONSES TO RIPARIAN LOGGING

There are hundreds of journal articles, government reports, and graduate theses documenting the effects of logging on physical and biological components of aquatic ecosystems in the PNW. Numerous volumes provide detailed summaries of this information and help place present management perspectives in a historical context (Northcote 1969; Salo and Cundy 1987; Meehan 1991; Naiman 1992; FEMAT 1993; Hogan et al. 1998). Figure 2 is a generalized representation of how seven physical and biological variables change through time following harvest of a mature/old-growth riparian zone forest. Similar curves can be drawn for other physical and biological components (Gregory et al. 1987), but here I consider only those that are commonly reported and used in the meta-analysis.

Following riparian logging, the increase in incident solar radiation results in an increase in water temperature. Within a few decades, water temperature is expected to return to normal as shrubs and deciduous trees shade the channel. Suspended and/or fine sediment loads may increase immediately due to logging activities (roads, yarding, etc.) and persistently due to the reduction in bank stability caused by the loss of root strength following tree removal. Large Woody Debris (LWD; generally defined as any piece of wood longer than 1 m and wider than 10 cm) volume and habitat complexity (generally a measure of pool frequency or percent area/volume) may not change immediately after logging, but as existing LWD is removed by floods and/or physical/biological decay, both LWD volume and habitat complexity are expected to decline below pre-harvest levels. A return to pre-harvest levels may not occur until new trees reach the age/size of the original riparian forest, which may take hundreds of years in the PNW (Franklin and Dyrness 1988; Murphy and Koski 1989). Some authors have observed that LWD loads increase following riparian harvest due to a pulse input of logging debris to the active channel (Bisson et al. 1987; see dotted line in Figure 2).

Primary productivity increases with solar radiation immediately following logging and declines to pre-harvest levels as the canopy closes and the channel becomes shaded. Until canopy gaps are created due to self-thinning, primary productivity may be lower than pre-harvest levels. Changes in macroinvertebrate biomass are expected to mirror those in primary productivity, though the relative abundance of different trophic guilds may change through time (Erman et al.1977; Gregory et al. 1987). For example, an increase in primary productivity may increase the abundance of primary consumer guilds more than that of predators.

Fish biomass (generally reported as the abundance, density, or growth rate of juvenile salmonids) often increases along with the increase in primary and secondary (macroinvertebrate) productivity. As primary productivity declines to pre-harvest levels and physical habitat degrades, fish biomass is expected to decrease below pre-harvest levels. As with macroinvertebrates, the relative abundance of different fish species may change following riparian harvest (Bisson et al. 1992; Reeves et al. 1993). If initial temperature increases approach a species' lethal limit, fish biomass may decrease instead of increase immediately following logging (dotted line in Figure 2; Hall and Lantz 1969; Young et al. 1999).

It is important to appreciate that the curves of Figure 2 do not predict how any individual stream ecosystem will respond to riparian logging. How the different physical and biological components of a stream ecosystem change following riparian logging will depend on climate, geology, bank full width, gradient, natural disturbance history, species composition, as well as the cumulative effects of anthropogenic and natural disturbance events throughout the watershed (Bisson et al. 1992). One of the goals of the meta-analysis is to quantify how climate (as approximated by latitude), stream gradient, and bank full width mediate the effects of riparian logging on different physical and biological components of stream ecosystems.

4. ECOSYSTEM FUNCTION AND RIPARIAN BUFFER WIDTH

There is no doubt that the removal of riparian vegetation affects stream ecosystems and that riparian buffers help mitigate those effects (Castelle et al. 1994; Davies and Nelson 1994). However, there is little empirical information on how different physical ecosystem components depend on riparian forest width. Furthermore, while some studies have compared various biological components of streams subject to logging with and without riparian buffers (e.g. Hall et al. 1987; Newbold et al. 1980; Murphy et al. 1986), I know of no published studies from the PNW that systematically compare biological components of stream ecosystems with *different* widths of riparian buffers. Presently, there is a study underway in southwestern British Columbia that will attempt to address this issue (Feller and Richardson 1999).

Figure 3 shows generalized functional relationships between different physical ecosystem components and riparian forest width measured as a fraction of the maximum site-specific tree height (STH-30-50 m for the central coast of British Columbia) (FEMAT 1993; Naiman et al. 2000). Bank stability depends primarily on live tree roots (and substrate type) and should be protected by relatively narrow buffer widths. Most LWD and Small Woody Debris (SWD) entering a channel originate within approximately 0.5 STH, but protecting natural level of organic debris input requires buffer widths of approximately one full STH (horizontal distance). Most shade is provided by trees within 0.5 STH of the channel, though trees beyond one STH can still provide shade to the wetted channel. Maintaining near-channel microclimate (air temperature, humidity, wind) requires buffer widths beyond one STH.

There are a number of important issues concerning the curves of Figure 3. First, these curves are derived from a handful of studies (see figure caption), only some of which are empirical. Second, as with Figure 2, these curves are general and do not predict how the physical ecosystem components of any particular stream depend on riparian forest width. Third, and perhaps most importantly, these curves do not account for disturbance events and other watershed processes operating at ecologically relevant spatial and temporal scales. LWD may be introduced from tributaries, or from distances far greater than one STH as a result of land slides. Water temperature depends on hillslope and riparian zone conditions higher in the watershed. Unconstrained channels migrate across the valley floor as banks erode, meaning trees hundreds of meters from the active channel are potential sources of future LWD (Fetherston et al.1995; Naiman et al. 2000). Fourth, at present there are no data from which to draw similar graphs for biological ecosystem components. To the extent that biological processes depend on the physical environment, we can infer what width of buffer zone is required to fully protect biological components, but the shapes of such curves remain unknown (Young 2000).

I hoped to use the meta-analysis to create curves like those in Figure 3 for the three commonly measured biological components of stream ecosystems. After reviewing hundreds of references, it became clear that the necessary data either do not exist or have not been communicated. Nevertheless, information from other regions (Davies and Nelson 1994), the relationships of Figure 3, and hundreds of years of cumulative experience and expertise have led to a general consensus that protection of aquatic ecosystems at the watershed scale requires riparian buffer widths of at least one STH for hillslope constrained channels capable of transporting water, sediment, and organic debris over ecologically relevant time scales (i.e. hundreds to thousands of years) (see reviews in: FEMAT 1993; Pollock and Kennard 1999; Young 2000). For unconstrained channels, the entire valley bottom should be managed as "riparian zone" in order to ensure that forest-stream linkages operate naturally over ecologically relevant time scales (Gregory et al. 1991; Naiman et al. 1992, 2000; Fetherston et al. 1995).

5. A META-ANALYSIS OF THE EFFECTS OF RIPARIAN ZONE LOGGING ON STREAM ECOSYSTEMS IN THE PACIFIC NORTHWEST

Meta-analysis is the quantitative synthesis, analysis, and summary of studies addressing the same subject (Hedges and Olkin 1985), and has become increasingly popular as the number of published studies increases (see special feature in *Ecology* 1999:80(4)). The approach is simple and allows general conclusions to be drawn about ecological phenomena studied by different scientists under different conditions. The results of individual studies are summarized by a single measure of "effect size", each of which serves as an independent observation in the meta-analysis. Meta-analysis is a four part process. (1) The criteria for acceptable studies are established. (2) A search for studies meeting those criteria is conducted. (3) A measure of effect size is calculated for each study, along with information on other variables of interest. (4) The effect size data are analyzed and conclusions are drawn.

5.1 *Study Criteria*

I included studies with data on seven ecosystem variables: water temperature, fine sediment load, large woody debris abundance (LWD), habitat complexity, primary productivity, macroinvertebrate abundance/production, and fish abundance/production. I required that studies be from the PNW (Figure 1) and meet two additional criteria. (1) The study must involve a direct comparison between streams with old-growth or mature second growth riparian forests and streams with harvested riparian zones. (2) The authors needed to provide information (either a time or a time range) on the time since riparian zone logging. These criteria eliminated many of the classic studies which informed the construction of the generalized curves in Figure 2 (e.g. Hawkins et al. 1983; Bilby 1984; Elliot 1986; Andrus et al. 1988; Bilby and Ward 1989; Murphy and Koski 1989; Ralph et al. 1994; Montgomery et al. 1995; Hetrick et al. 1998a, 1998b; Keith et al. 1998).

Three study designs (or combinations thereof) were accepted for use in the meta-analysis. (1) *before-after* studies: the same stream was monitored before and after riparian logging. (2) *paired site* studies: multiple paired sites, each with an unlogged reach and a reach whose riparian zone had been logged at some time (range) before data were collected. (3) *extensive post treatment* studies: multiple streams within a region where the riparian zone of each site was either undisturbed or logged at some time (range) before data were collected.

5.2 *Literature search*

I searched my personal collection of papers, reports and theses, and requested papers from colleagues' collections that met the two criteria. Additional searches of various data bases on World Wide Web were conducted using the following key words and combinations thereof: Pacific Northwest, riparian, logging, temperature, sediment, large woody debris, primary productivity, invertebrates, macroinvertebrates, and fish. Searched data bases included: Science Citation Index 1989-present, the ecology journals of JSTOR 1900-1995, and TREE abstracts of forest science.

5.3 *Effect size calculations*

Data were taken from tables when possible. Otherwise data were taken directly from the text or from figures by calibrating the axes and transforming the value from millimeters to the units of the variable of interest. For each of the seven variables reported, I calculated the response ratio, $R = X_L/X_C$, where X_L and X_C are the values (or the sample mean) of the logged and control sites, respectively. I then transformed the response ratio to $L = \ln(R) = \ln(X_L) - \ln(X_C)$, which linearizes the metric by treating deviations in the numerator the same as deviations in the denominator, and produces a more normal distribution than R for small sample sizes (Hedges et al. 1999). Given the scale and cost of studying stream ecosystems, many X_L and X_C values were single observations, not sample means. Furthermore, many authors did not report measures of dispersion or sample sizes when X_L and X_C were sample means, so I was unable to weight or calculate confidence intervals for most L values. In an effort to include as many studies as possible, I included all estimates of L that met the search criteria, which compromised accuracy for information (Gurevitch and Hedges 1999).

Response ratios were calculated differently for the different study designs. For before-after studies with more then two years of data, I simply calculated the mean value of the response variable before and after riparian logging and calculated L as above. For paired site designs I calculated the response ratio for each site pair, then calculated L as the mean of those values. This approach is appropriate for estimating the effects of riparian logging because it controls for variation between different pairs of sites. For extensive post treatment studies I calculated L as described above. If studies combined paired site and before-after designs, I calculated the response ratio for every year data were reported, then designated the mean response ratio before riparian zone logging as X_C. For each year after riparian logging, I calculated the response ratio, then divided this value by the pre-harvest mean response ratio. Thus, if there was no effect of harvesting, $L = 0$.

Every response ratio is associated with two continuous variables: latitude and time since riparian logging. One of the goals of the meta-analysis is to determine how different environmental conditions affect the responses of the seven variables to riparian logging. When the authors provided the necessary information, I also classified response ratios by stream gradient (low < 5%, high >5%), bank full width (small < 5m, large >5m), and whether or not there was a riparian buffer zone.

5.4 *Data analysis*

Thirty-four studies met the search criteria and were used in the meta-analysis (Figure 1; Appendix A). In some cases data from the same study were reported in different paper. I chose sources based on the completeness and accuracy of reporting. Many studies reported data for more than one of the seven variables. For many studies I was able to calculate more than one independent response ratio for the same variable based on gradient and bank full width classifications. I was able to calculate a total of 121 response ratios.

Because the response ratios for different variables were often from the same study areas (though sometimes from different studies), only a small sub-set of the seven types of response ratios qualified as true independent observations. For this reason I analyzed the response ratios for each of the seven ecological components separately. Small sample sizes prevented me from conducting fully factorial analyses. Instead, I conducted a series of ANCOVAS (Type I Sums of Squares) with $L = \ln(R)$ as the dependent variable. Each model included, in the following order, a factor (buffer-no buffer, low-high gradient, small-large bank full width), $\log_{10}$(time) as a covariate, and an interaction term. The effects of gradient and size were similar, which is expected because narrow streams tend to have high gradients. For graphical clarity I show the transformed response ratios (L) for four stream types (small, large, those with riparian buffers, and those with no buffer or size information) on the y-axis with time since riparian logging (untransformed) on the x-axis.

5.5 *Results*

The results of the meta-analysis are shown in Figures 4-7. Note that the values on the *y*-axes are different for the seven variables. Preliminary analyses indicated that latitude did not influence the effect of riparian logging on any of the seven variables.

Riparian zone logging increased water temperatures immediately (0-10 years) following harvest (Figure 4). Riparian buffers moderated this effect ($P < 0.10$). There were only two response ratios beyond 20 years, but the data suggest that water temperature returns to normal within a few decades.

Fine sediment loads increased following logging but none of the factors affected the magnitude of the response ratio (Figure 4). Again, there are only two data points beyond 20 years. No temporal trend in fine sediment load is apparent. However, if the two data points beyond 20 years are removed, fine sediment loads appear to return to pre-harvest levels soon after logging.

The effect of riparian logging on LWD load depended on stream size ($P < 0.01$) (Figure 5). In small streams there was an increase in LWD load after logging, followed by a decline through time to pre-harvest levels. In all six cases, riparian logging decreased LWD loads in large streams. Though there are only two data points, riparian buffers appear to ameliorate the effect, whether positive or negative, of logging on LWD loads.

Riparian logging tended to decrease habitat complexity in large streams and increase habitat complexity in small streams ($P = 0.10$) (Figure 5). For small streams, habitat complexity appeared to remain at or above control levels through time. No temporal trend was apparent for large streams. LWD load and habitat complexity showed similar patterns of change following riparian zone logging, though the response ratios for LWD load are much larger than those for habitat complexity. This result is expected because LWD plays a key role in creating pools and off-channel habitats, but the effect of LWD on habitat complexity is likely asymptotic. The increase in both response ratios for small streams probably results from LWD being introduced the channel during logging (see dotted line in Figure 2). The same probably occurs in larger streams, but higher flows and wider channels likely resulted in natural and introduced LWD being removed downstream soon after logging.

Riparian logging increased primary productivity and macroinvertebrate biomass (Figure 6). In both cases, the few data beyond 10 years suggest the effects of logging decrease through time. Lack of data made it impossible to test for the effects of buffer zones or stream size on either variable. However, high gradient streams showed a greater increase in primary productivity following riparian logging ($P < 0.05$; data not shown). Since high gradient streams tend to be small, have closed canopies, and dominated by heterotrophic energy pathways, this result supports the idea that the effect of riparian logging on energy pathways is more pronounced in small streams (Vannote et al. 1980).

Fish biomass tended to increase following riparian logging and return to control levels through time (Figure 7). None of the factors affected the magnitude or temporal pattern of this response.

6. DISCUSSION

The results of the meta-analysis are broadly consistent with the generalized curves shown in Figure 2. The response ratios for water temperature, primary productivity, and macroinvertebrate biomass increase immediately following riparian logging and show evidence of decreasing to zero (no effect) within a few decades. Similarly, fish biomass tends to increase following logging, then return to control levels through time. The effect of riparian logging on LWD loads and habitat complexity depended on stream size. Fine sediment loads increase following logging, but the response ratios show no temporal pattern and were not influenced by any of the stream level environmental factors. Taken together, the generalized curves of Figure 2 and the results of the meta-analysis suggest that: (1) research over the last 40 years has provided us with general conceptual framework for understanding the effects of riparian timber harvest on aquatic ecosystems, (2) some of the variation in aquatic ecosystem response to riparian logging is explained by stream size and/or gradient, and (3) there is considerable variation in the response of stream ecosystems to riparian logging.

In the context of developing a decision tool for riparian zone management, I suggest that this final point is the most important. Because the response of stream ecosystems riparian zone logging is variable, it will be logistically difficult, conceptually daunting, and prohibitively expensive to develop (and judge the efficacy of) riparian zone management strategies using a stream-by-stream approach. I believe that these facts argue for the need to adopt a watershed based approach to riparian zone management and associated monitoring efforts. In the end, we should be managing to protect the structure and function of entire lotic ecosystems (watersheds), not only their component parts (streams).

There are at least three sources of error, two methodological and one ecological, that likely contribute to the disparities between the curves of Figure 2 and the results of the meta-analysis (Figures 4-7). The first source of error exists in any data synthesis, whether qualitative or quantitative; no two studies follow the exact same methodology (Gurevitch and Hedges 1999). This is more problematic for studies of forestry-fisheries interactions than for studies using traditional experimental designs. Researchers used different variables to describe the seven ecological components of stream ecosystems, and they collected their data during different times of the year (although for consistency I used data from summer months whenever possible). Logging methods were generally poorly described, and surely differed among studies. Some response ratios were calculated from single observations, which results in a small "ecological signal" to "climatic/stochastic noise" ratio in the data. Finally, the degree of logging activity within the watersheds of the treatment and control streams was rarely reported, and certainly varied both within and between studies. Thus, the effects of riparian timber harvest on the study sites were confounded by ecological processes operating at the watershed scale.

The second source of methodological error is unique to this meta-analysis. The response ratios and their associated "time since riparian logging" were often mean values. For before-after studies, I often calculated the mean response ratio and mean "time since riparian logging" from multiple post-treatment observations. For paired site and extensive post treatment studies, authors usually only reported a range (or mean time) for "time since riparian logging" (eg., "sites were logged 40-60 years before"), from which I took the middle of the range as the "time since riparian logging". Thus, many of the points in Figures 4-7 do not have a true "time since riparian logging". Both procedures were required to produce independent observations for use in the meta-analysis.

I believe the third source of error is due to natural variation in stream ecosystems resulting from processes operating at two different spatial scales. First, the response of a stream ecosystem to riparian zone logging depends on the initial conditions of the study site. The local disturbance history of the site(s) will influence how different ecological components change following riparian timber harvest. For example, if a large flood occurred before the study, LWD loads and fish populations may be relatively low, and the effect of timber harvest on these variables would be small or large, respectively. Alternatively, if the site(s) had been free of natural disturbance for centuries before the study began, the effects of riparian timber harvest may be the opposite. Second, processes operating at the watershed scale can influence site-specific conditions, and thus impart partial control over ecosystem response to riparian logging. That is, a site's fine sediment load, LWD load, habitat characteristics, and fish population all depend on watershed conditions and processes that are impossible to control in field studies. This may be less true for primary productivity, macroinvertebrate biomass, and (particularly in small streams) water temperature, which should depend more on site-specific conditions. It is not surprising that the response ratios for these three variables were more consistent with the generalized curves of Figure 2.

Two final points related to ecological error warrant mention. First, the data used in the meta-analysis do not span the time scales relevant to stream ecosystems and watershed processes in the PNW (see Figure 2). The "longest" studies measured components of stream ecosystems logged only 50 years before data collection. For example, it would be inappropriate to conclude from the meta-analysis that fish populations are not negatively affected by riparian zone logging. While there is convincing evidence for the negative long-term (hundreds of years) cumulative effects of timber harvest on lotic ecosystems (Bisson et al. 1987, 1992; FEMAT 1993), no explicitly comparative studies of the long-term effects of riparian zone logging are available. Second, the few long term before-after studies that quantify the effects of riparian logging speak to the complexity of ecological responses. For example, the Carnation Creek study on Vancouver Island, British Columbia, which was included in the meta-analysis despite being poorly designed from a riparian logging perspective, produced dozens of papers and reports. In addition to the logging treatments of interest, scientists were required to consider terrestrial climate, ocean conditions, catastrophic disturbance events, and life history variation of the fish species in order to explain the various ecological responses. While much of the variability in the data analyzed in the meta-analysis can be explained by detailed study of site-specific conditions, it is financially unreasonable and ecologically dubious to expect forestry companies to invest the human and economic capital necessary to conduct riparian zone management on a stream-by-stream basis.

7. CONCLUSIONS

- *Riparian zone logging affects different components of stream ecosystems differently through time*. The generalized curves (Figure 2) developed from over 40 years of research in the PNW are empirically based, conceptually sound, and in broad agreement with 34 studies that directly measure the effects of riparian timber harvest on stream ecosystems.

- *Empirical and theoretical studies suggest that most of the* ***physical*** *functions associated with riparian-stream linkages can be maintained with riparian no-harvest zones of approximately one site specific tree height* measured from the edge of the active channel for hillslope constrained streams, and the edge of valley bottom for unconstrained channels. This conclusion is based on stream level processes and **does not account** for the effects of watershed processes on the physical components of stream ecosystems.

- *There is little empirical information from the PNW relating* ***biological*** *functions to the width of riparian no-harvest zones*. Assuming that biological processes depend on physical conditions, the full suite of biological functions will probably be protected by similar widths of riparian no-harvest zones. However, the shapes of such functional curves are unknown.

- *The meta-analysis suggests there is substantial variation in the response of stream ecosystems to riparian logging*. Some of this variation can be attributed to channel type. Some of the variation likely arises from differences in experimental methods. The remaining variation probably results from differences in site-specific conditions, disturbance histories, and watershed processes.

8. RECOMMENDATIONS

The recommendations below are based on my (widely shared) belief that ecologically sustainable riparian zone management should be: simple, operationally flexible, applied at the watershed scale, and guided by conditions observed in unmanaged watersheds (that is, it should *ecologically precautionary*). The central coast of British Columbia is perhaps the last place in the PNW, and one of last on earth, where we have the opportunity to practice forestry in an ecologically, economically, and socially sustainable manner. Doing so will require reduced harvest rates, a fundamental change in our temporal view of sustainability, and a recognition that the economic value of trees is far greater than the fiber they provide. **Our challenge is to maintain the forestry, fisheries, and tourism economies of the central coast not for decades, but for centuries.**

- *Individual streams should not be managed for any single ecological "endpoint", but rather for the capacity to oscillate within a natural range of physical and biological conditions*. The ecological characteristics of streams vary naturally through time. Channels are hierarchically connected at the watershed scale. The physical and biological characteristics of streams depend in part on conditions higher in the watershed. Stream ecosystems should be protected if we manage riparian zone forests in a way that maintains watershed health: **"Ecologically healthy watersheds require the preservation of lateral, longitudinal, and vertical connections between system components as well as the natural spatial and temporal variability in those components"** (Naiman et al. 1992).

- *Ecosystem based riparian zone management must consider the temporal scale of relevant ecological processes*. Watershed processes operate over tens to hundreds, even thousands, of years. The commercial tree species of the central coast of British Columbia live hundreds of years. Large scale disturbance events are rare, resulting in a pattern of small patches of young trees in a matrix of "old growth" forest. These older trees provide the **large** organic debris that determines the physical and biological character of aquatic habitats. Aquatic species have adapted for at least 6,000 years to these conditions, and their long-term persistence logically depends on maintaining such conditions. Riparian zone management strategies and associated monitoring programs must acknowledge and incorporate these ecological realities.

- *Riparian zone management should be conducted at the watershed scale*. The goal of ecosystem based riparian zone management should be to maintain within natural ranges the input and routing of water, sediment, and organic debris through the channel network. In order to ensure that aquatic ecosystems function naturally, the rate and spatial extent of riparian zone timber harvest should be constrained by natural disturbance regimes operating over *all relevant spatial and temporal scales*. The species composition, and spatial and age-class structure of riparian zone forests in managed watersheds should be similar to those observed in unmanaged watersheds.

- *The retention requirements of an ecosystem based "Riparian Decision Tool" should be imposed at the watershed scale*. Decisions regarding the spatial distribution of riparian zone logging within a watershed should be left to operator, yet be informed and constrained by the distribution of aquatic species (e.g. salmon) and the need to "preserve physical and biological linkages between streams, riparian zones, and upland areas" (Bisson et al. 1992). Protecting these ecological linkages in an economically viable way in the central coast of British Columbia will require abandoning stream-level approaches to riparian zone management in favor of an operationally flexible watershed approach.

- *Riparian zone management should incorporate experimental designs that are likely to improve our understanding of the effects of riparian zone logging on aquatic ecosystems.* The unmanaged watersheds of the central coast of British Columbia provide an unparalleled opportunity for conducting watershed level experiments. If we choose to continue manipulating such watersheds, we should do so in a way that creates knowledge in addition to jobs.

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APPENDIX A: studies used in the meta-analysis of the effects of riparian zone logging on seven components of stream ecosystems.

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