Buffering the Buffer[1]

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Abstract: *Riparian buffer strips are a widely accepted tool for helping to sustain aquatic ecosystems and to protect downstream resources and values in forested areas, but controversy persists over how wide a buffer strip is necessary. The physical integrity of stream channels is expected to be sustained if the characteristics and rates of tree fall along buffered reaches are similar to those in undisturbed forests. Although most tree-fall-related sediment and woody debris inputs to Caspar Creek are generated by trees falling from within a tree's height of the channel, about 30 percent of those tree falls are triggered by trees falling from upslope of the contributing tree, suggesting that the core zone over which natural rates of tree fall would need to be sustained is wider than the one-tree-height's-width previously assumed. Furthermore, an additional width of "fringe" buffer is necessary to sustain appropriate tree-fall rates within the core buffer. Analysis of the distribution of tree falls in buffer strips and un-reentered stream-side forests along the North Fork of Caspar Creek suggests that rates of tree fall are abnormally high for a distance of at least 200 m from a clearcut edge, a distance equivalent to nearly four times the current canopy height. The appropriate width of fringe buffer needed to protect the core zone will need to be determined using an analysis of the long-term effects and significance of accelerated tree-fall rates after logging.*

Riparian buffer strips provide an efficient and widely accepted way to help protect aquatic ecosystems and downstream values from the effects of upslope land-use activities. Buffer strips are also the focus of a major controversy concerning the appropriate balance between rights and responsibilities, between resource extraction and resource protection. The question at the center of the controversy: how wide should a buffer strip be? Here we first discuss the roles intended for riparian buffer strips and then describe preliminary results of a study that examines the stability of riparian buffer strips.

The Role of Riparian Buffers

Riparian buffer strips are intended to allow natural interactions between riparian and aquatic systems to be sustained, thus providing some assurance that appropriate in-stream ecosystems, sediment regimes, and channel forms can be maintained. Specific roles of riparian zones—and particularly of riparian trees—with respect to the in-stream environment include:

- Maintenance of the aquatic food web through provision of leaves, branches, and insects
- Maintenance of appropriate levels of predation and competition through support of appropriate riparian ecosystems
- Maintenance of water quality through filtering of sediment, chemicals, and nutrients from upslope sources
- Maintenance of an appropriate water temperature regime through provision of shade and regulation of air temperature and humidity
- Maintenance of bank stability through provision of root cohesion on banks and floodplains
- Maintenance of channel form and in-stream habitat through provision of woody debris and restriction of sediment input
- Moderation of downstream flood peaks through temporary upstream storage of water
- Maintenance of downstream channel form and in-stream habitat through maintenance of an appropriate sediment regime

Riparian zones thus are important to adjacent in-stream ecosystems because they strongly control the availability of food, distribution of predators, form of channels, and distribution of stream temperatures (Murphy and Hall 1981, Naiman and Sedell 1979, Theurer and others 1985, Zimmerman and others 1967). They are important for downstream environments because they regulate the type and amount of sediment coming from upslope and upstream, moderate downstream flood peaks, and provide organic material for downstream channels (Masterman and Thorne 1992, Trimble 1957, Vannote and others 1980).

Of these roles, that of maintaining appropriate channel form is particularly important both for sustaining aquatic ecosystems and for controlling off-site impacts. Large woody debris is a critical physical component of forestland channels because it traps sediment and dissipates flow energy. In the smallest channels, woody debris can stabilize landslide debris, store sediment, and provide "check-dams" to prevent gullying. In larger channels, wood can trigger the accumulation of spawning gravel, create backwaters, and cause pools to form. The ability of woody debris to perform these roles is influenced strongly by the input rate, species composition, and size distribution of in-falling trees. As these characteristics deviate from natural values, channel form—and, therefore, in-stream habitat—will change to reflect the altered

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woody debris regime (Lisle and Napolitano, these proceedings).

From a policy point of view, riparian buffer strips are important because they are a demonstrably successful means of protecting in-stream ecosystems (Davies and Nelson 1994, Erman and others 1977, Murphy and others 1986). Their importance stems from an awkward truth about aquatic ecosystems: these systems are complicated. It has become clear over the past several decades that the more an aquatic ecosystem is studied, the more is discovered about previously unrecognized critical habitat needs. Thirty years ago we did not understand the importance of large woody debris; 20 years ago we were ignorant of the need for off-channel rearing and refuge habitat for salmonids. We can thus assume that we do not yet know everything about the habitat and ecosystem characteristics needed for the survival of coho salmon and other aquatic species. Given this level of uncertainty, it is necessary to maintain a habitat system that functions similarly to that in which a species evolved if that species is to be sustained. If a riparian buffer strip is wide enough to ensure that a channel system does not receive biological and physical signals that upslope conditions have changed, the aquatic system is likely to be capable of providing the habitat and resources required to sustain its full complement of species.

The Forest Ecosystem Management Assessment Team report (FEMAT 1993) describes the need for this ecosystem-based strategy for species conservation: "...any species-specific strategy aimed at defining explicit standards for habitat elements would be insufficient for protecting even the targeted species. To succeed, any...[s]trategy must strive to maintain and restore ecosystem health at watershed and landscape scales." FEMAT thus advocated the establishment of riparian reserves to help sustain the proper functioning of processes that influence habitat, and thus to provide for both known and as-yet-unknown habitat requirements for coho and other aquatic species. FEMAT recommendations were incorporated into the Northwest Forest Plan (USDA and USDI 1994), which applies to federal lands in the Pacific Northwest. A report prepared for the National Marine Fisheries Service (Spence and others 1996; known as the "ManTech report") makes similar recommendations for the design of Habitat Conservation Plans on non-federal lands in the same area.

The width of riparian strip needed to fulfill each of the roles listed above depends on the kind of riparian community present, the type of stream, and the role in question. Appropriate widths often are reported in terms of the height of trees that would grow in the zone under natural conditions. In the case of the FEMAT report, this "site potential tree height" is defined as "the average maximum height of the tallest dominant trees (200 years or older) for a given site class." Under the Northwest Forest Plan, prescribed buffer widths for fish-bearing streams are a minimum of two tree heights' width, while the ManTech report concludes that buffers equal to or greater than one tree height's width are necessary, depending on which riparian functions are to be maintained. Similarly, the Sierra Nevada Ecosystem Project's discussion of riparian needs recommends a minimum of a one-tree-height buffer (Kondolf and others 1996). All of these recommendations specify that management activities such as logging and road-building are to be avoided within riparian zones unless those activities are compatible with the restoration and preservation of appropriate riparian and aquatic function.

Although there thus appears to be some consensus among the technical and scientific communities about riparian protection needs in support of aquatic ecosystems, controversy continues because of the implications of such protection for resource extraction opportunities. In a terrain with a stream density of 3 km/km^2, 15 percent fish-bearing channels, and a 50-m site-potential tree height, Northwest Forest Plan riparian reserve areas for fish-bearing streams would account for approximately 8 percent of the area, and lesser requirements for non-fish-bearing streams would represent an additional 20 to 25 percent. Buffer strips would thus occupy a substantial portion of the landscape. The rationale for requiring buffer strips must be well-founded if such prescriptions are to be willingly followed.

Both the FEMAT and ManTech reports distinguish between buffer-strip widths necessary to sustain the physical stream environment and those needed to sustain near-channel microclimate and appropriate riparian communities. Both reports note that trees farther than one tree height from the stream are unlikely to contribute wood or sediment to the stream, so the physical integrity of the stream system is likely to be sustained if appropriate tree-fall characteristics and rates are maintained within a buffer strip of width equivalent to one tree height. Both also note that the microclimatic conditions that strongly influence riparian communities and affect stream temperatures are potentially influenced by altered conditions to a distance of two to three tree heights from the edge of the buffer strip. The strategies thus call for maintenance of an essentially undisturbed vegetation community within one or more tree-heights' distance from perennial or fish-bearing streams. The ManTech report further indicates that an extra width of buffer may be needed to protect this core buffer from accelerated mortality due to the presence of the edge.

Approach

The goal of the study described here was to evaluate the influence of a newly established forest edge on rates of sediment and woody debris input to a stream channel. This information might then be used to evaluate the width of riparian buffer strip needed to sustain the physical functioning of the channel system.

Studies in Oregon (McDade and others 1990, VanSickle and Gregory 1990) and Alaska (Murphy and Koski 1989) demonstrate the relative importance of in-falling trees as a function of distance from a channel: trees near the stream have a much greater likelihood of introducing woody debris than do those farther away *(fig. 1)*. Because introduction of woody debris disturbs banks and diverts channel flows, in-channel erosion is likely to be modified by in-fall, and the sediment input triggered by this source is likely to vary with distance from the channel in the same way as input of woody debris. The first objective of this study was to define variations in wood and sediment input to channels as a function of the distance of the source tree from the channel.

Along the outer edge of the buffer, the most exposed trees are expected to be most susceptible to windthrow, microclimatic stress,

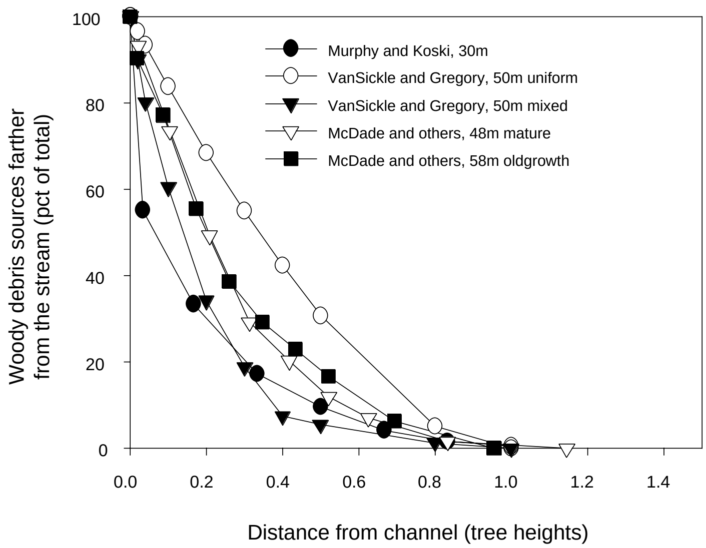

Figure 1—Location of woody debris sources with respect to channel edges. Measurements by Murphy and Koski (1989) were reported by Spence and others (1996) to have been from a forest with a 30-m canopy height; results from VanSickle and Gregory (1990) are modeled; results from McDade and others (1990) are from field measurements.

damage by felling and yarding of nearby trees, and insect infestation and disease associated with increased stress and damage. Farther into the stand, lesser exposure is expected to decrease the probability of mortality until, at some distance, mortality rates would reapproach those characteristic of the interiors of undisturbed stands. It is possible, also, that mortality rates would then increase again near channels in both disturbed and undisturbed stands as a result of channel erosion, seasonally saturated soils, increased prevalence of shorter-lived riparian hardwoods, and locally steep banks associated with inner gorges. A second objective of this study thus was to define the relation between tree-fall mortality and distance from a riparian buffer edge.

Buffer widths appropriate for sustaining the physical characteristics of the stream channel then could be designed using these two kinds of information. The minimum width of the core buffer could be selected as the maximum distance from which tree-fall sediment and debris enter the stream *(fig. 2),* and the minimum width of the fringe buffer would be the distance over which edge effects influence rates of tree fall inside a stand *(fig. 2).* The final objective of the study was to use the results of the first two objectives to estimate core and fringe buffer widths that would be capable of sustaining an appropriately functioning riparian buffer that is itself capable of maintaining an appropriately functioning physical stream environment.

The Field Site

Field work was carried out in the 3.8-km^2 North Fork Caspar Creek watershed above the Arfstein gauging station on the Jackson

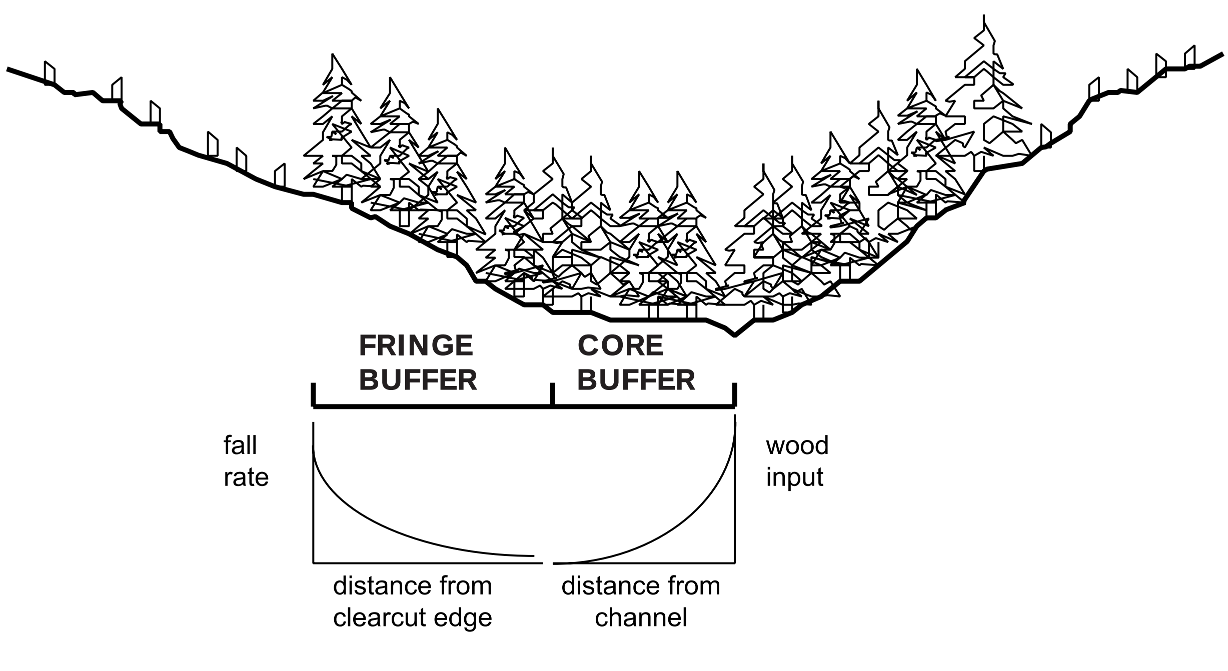

Figure 2—Hypothetical example of “core” and “fringe” buffer zones intended to sustain the physical integrity of the channel system. The core zone extends from the channel to the maximum distance of sediment or wood input from falling trees, and the fringe zone extends beyond the core far enough to maintain appropriate tree-fall rates within the core zone.

Demonstration State Forest, Mendocino County, California *(fig. 3).* The watershed is underlain by Cretaceous to Oligocene sandstones and shales of the Franciscan assemblage, on which are developed loam soils which typically have depths of 50 to 200 cm. Drainage density is about 4 km/km^2, and portions of the streams are inset into locally developed inner gorges. Valley-bottom width along the mainstem channel generally ranges between 5 and 15 m, and, where developed, inner gorge slopes have slope-lengths of about 40 to 100 m and gradients of 30° to 40°. Hillslopes beyond the inner gorge range in gradient between 15° and 30° with a maximum slope length of about 350 m.

Rainfall in the area averages about 1200 mm/yr, and 90 percent of the annual precipitation falls during October through April. Snow is uncommon. Rain falls primarily during frontal storms of one or more days' duration, and rain is ordinarily preceded by periods of high-velocity southerly to south-westerly winds. Major tree-fall events are associated with these winter storms.

The original forest was dominated by coastal redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies grandis*); tanoak (*Lithocarpus densiflorus*) would have been present in the understory. Most of the watershed was first clearcut and burned between 1864 and 1900 (Henry, these proceedings; Napolitano, these proceedings). The second-growth forest is thus on the order of 90 to 130 years old, and consists of natural regeneration of the original species. About 55 percent of the stems greater than 15 cm in diameter are redwood, 26 percent Douglas-fir, 10 percent tanoak, and 5 percent grand fir. About 61 percent are less than 0.5 m in diameter, and 7 percent are greater than 1 m. Many of the original redwoods resprouted from stumps, forming clumps of young redwoods surrounding the original boles. Land in the area is considered to be of site class II for redwood, indicating that 100-year-old redwoods are expected to be 47 to 55 m high (CDF 1998). Measured lengths of fallen canopy trees indicate that average canopy height is currently about 50 to 60 m.

The second cycle of logging began in 1989 under a protocol designed for a cumulative effects experiment (Henry, these proceedings). About 43 percent of the watershed was clearcut over a 3-year period in blocks of 9 to 60 ha. Stream-side buffer zones 30 to 60 m wide (a distance equal to approximately 0.5 to 1 tree heights) were left along the mainstem channel. About 35 percent of the volume of standing wood was removed selectively from the outer portion of these strips, with the trees selected for removal being those either expected to have a high probability of falling or those at an optimum condition for wood production. Few if any trees were removed from within 15 m of the channel. Storms occurred during the winters of 1990, 1994, and 1995 that were associated with high rates of tree fall.

Methods

The study was conducted in three phases. First, all trees that had fallen or snapped since logging were counted in 10 sections of buffer strip and four uncut sample plots along the North Fork of Caspar Creek *(fig. 3, table 1).* One of the uncut plots was opposite a cut unit; the others were not. One buffer-strip plot was located on an old landslide scar, and another occupied a floodplain formed by infilling behind an old splash dam. Plots were selected to have similar orientations relative to the prevailing southerly direction of storm winds. Study plots ranged from 63 to 202 meters in length along the channel and extended to the edge of the buffer strip or, if uncut, to a 60-m slope distance from the channel. Surveys were conducted from March 1994 through May 1995, with plots associated with the

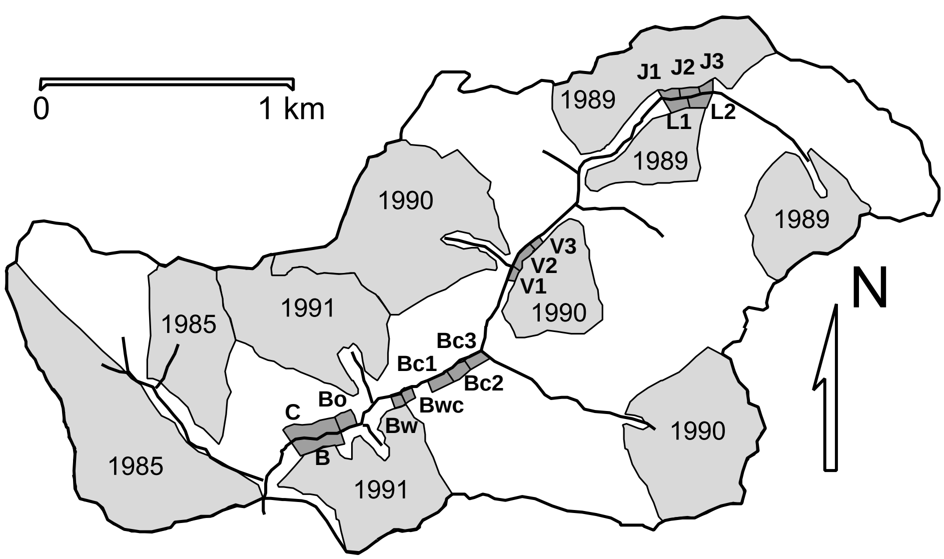

Figure 3—Location of the North Fork Caspar Creek tree-fall study plots, showing clearcut unit boundaries, year cut, study plots, and plot names. See table 1 for plot descriptions. Plot JL is located on the floodplain between the J plots and the L plots.

Table 1—Plot descriptions

Plot	Class	Area (ha)	Original trees/ha	Cut age	Pct. vol. cut	Original standing live trees	Thrown live trees	Snapped live trees	Pct. dead	Original standing snags	Downed snags	Meters from edge[2]	Method[1]
Bwc	Uncut	0.56	255	None	0	144	2	2	2.78	31	9	48	2
Bc1	Uncut	0.43	308	None	0	132	2	0	1.52	19	1	176	1,2
Bc2	Uncut	0.47	301	None	0	141	1	0	0.71	18	7	264	1,2
Bc3	Uncut	0.47	340	None	0	159	1	1	1.26	12	1	188	1,2
Bo	Opposite	0.48	434	1991	0	206	13	1	6.80	10	2	88	2
C	Opposite	1.21	345	1991	0	418	9	1	2.39	—	0	88	1
B	Buffer	1.21	266	1991	31	322	34	4	11.8	—	13	28	1
Bw	Buffer	0.19	258	1991	31	50	1	3	8.00	10	1	28	2
V1	Buffer	0.38	274	1990	22	103	5	1	5.83	8	3	16	1,2
V2a[3]	Buffer	0.14	388	1990	0	47	3	0	6.38	6	1	38	2
V2b[4]	Buffer	0.28	242	1990	33	68	12	1	19.1	—	1	15	1
V3[5]	Buffer	0.19	457	1990	<22	86	25	1	30.2	9	9	20	1,2
J1	Buffer	0.31	361	1989	35	112	3	1	3.57	7	6	13	1,2
J2	Buffer	0.24	413	1989	35	98	5	1	6.12	16	9	12	1,2
J3	Buffer	0.40	238	1989	35	95	4	1	5.26	4	3	18	1,2
L1	Buffer	0.33	345	1989	38	115	14	3	14.8	4	2	18	1,2
L2	Buffer	0.33	201	1989	38	66	12	0	18.2	5	3	19	1,2
JL[6]	Buffer	0.45	55	1989	0	25	1	0	4.00	0	0	40	1,2

[1]1: Original survey; 2: stand map
[2]Distance between edge of clearcut and center of plot
[3]Only the portion of the buffer within 15 m of the channel was mapped
[4]This portion of the buffer strip includes only the area of the original survey that was not mapped later
[5]Located on an old landslide
[6]Located on a floodplain created by a splash-dam

earliest logging being surveyed first. Plots originally surveyed in 1994 were resurveyed in 1995, so all surveys included all downed trees as of May 1995.

For each downed tree, a live control tree was selected at approximately the same distance from the bank by pacing a random number of paces upstream or downstream along the contour and choosing the nearest live tree. Data collected for each tree include species, diameter at breast height, damage class (snapped, thrown, or control), fall direction, whether the tree was dead when thrown or broken, estimated time since damage, distance to stream channel, distance to buffer-strip margin (if present), amount and type of wood input into the stream channel, amount of soil input to the stream channel, and the presence of factors that might be expected to increase the probability of a tree being thrown or broken. Possible contributing factors included seasonally saturated soils, steep slopes, root rot, whether a redwood was part of a sprout clump, bank and slope failures, logging damage, damage from another falling tree, and nearby road or trail construction.

Time since damage was known for most trees that fell in 1995 and for some trees that had fallen close to the channel in 1992 and 1993. For other trees, age was estimated from root sprouts or other vegetative evidence, or the tree was classified into one of five decay classes according to the condition of its foliage and branches: (1) green leaves or needles present, (2) dead leaves or needles present, (3) leaves gone but small twigs present, (4) small twigs gone but branches present, and (5) branches gone or bark sloughing off. Additional evidence, such as the age of vegetation on or around the root-wad, was used to eliminate trees that had fallen more than 5 years before the surveys. The decay classes were converted to approximate years since damage on the basis of comparison to fallen trees for which dates of fall were known by either direct observation or vegetative evidence.

The second study phase was carried out between May 1994 and December 1995. All standing and recently downed trees were mapped using a survey laser in 12 of the original survey plots (nine buffer zones and three controls) and in three additional plots, two in un-reentered stands and one in a small section of buffer *(fig. 3, table 1)*. Species, diameter, condition (live, snag, snapped when living, snapped snag, thrown), distance from channel, and distance from clearcut edge were recorded for each tree. The channel edge was also mapped, and the outer edge of the selectively logged buffer zone was defined as a line connecting the outermost trees at approximately 20-m intervals. The first two phases of the study together characterized tree falls representing a 6-year period.

A storm in December 1995 resulted in abnormally severe blowdown in the study area and provided an opportunity to collect an additional set of data for the third phase of the study. All trees were counted that were felled by the storm and contributed wood or sediment to the channel along 3 km of the mainstem of North Fork Caspar Creek. Each tree was characterized by species, diameter, sediment input, wood input, distance along the channel, distance from the channel, whether it was alive or dead when it fell, and whether it was hit by another tree. Trees felled by the December storm were not included in data sets from the other phases of the study.

Results and Discussion

Comparison of the populations of standing and fallen trees in the uncut study plots suggests that tanoak is the most susceptible species to tree fall, while redwood falls at a lower than average rate. Fall rates are distributed approximately according to the proportional representation of size classes. Data from the post-storm channel survey show no statistically significant differences in the species or size distribution between trees that entered the channel from buffer strips and those from un-reentered forest.

Two styles of tree fall were evident. Most common is failure of individual trees, which then may topple others as they fall. However, the sequence of storms since logging progressively contributed to extreme rates of tree fall in at least four locations in the watershed, suggesting the possibility that high-intensity wind eddies may have locally severe effects. In each of these cases, the area of concentrated blowdown was located within about 150 m of a clearcut margin. None of these sites were included in the sampled plots.

Most tree fall occurred by uprooting, with only 13 percent of failures caused by snapping of boles. Failure by snapping was particularly common among grand fir, but both Douglas-fir and redwood were also susceptible. The majority of trees fell downslope even when the downslope direction was opposite the direction of prevailing storm winds.

Measurements from the long-channel survey indicate that fallen trees influenced the stream channel by introducing woody debris from as far as 40 m from the channel in un-reentered forests and 70 m along buffer strips *(fig. 4)*. About 90 percent of the instances of debris input occurred from falls within 35 m of the channel in un-reentered forests and within 50 m of the channel in buffer strips. The pattern for un-reentered forests approximately follows the distributions measured by McDade and others (1990) for mature and old-growth forests *(fig. 1)*. However, the distribution predicted by VanSickle and Gregory (1990) for a mixed-age conifer forest *(fig. 1)* underrepresents the observed importance of trees falling from greater distances. This discrepancy is probably due to the observed tendency of Caspar Creek trees to fall downslope, whereas the modeling exercise assumed a random distribution of tree-fall directions (VanSickle and Gregory 1990). The distribution of source distances observed for buffer strips at Caspar Creek demonstrates higher rates of input at greater distances than measured or modeled previously, possibly reflecting the combined effects of high tree-fall rates in the selectively logged portion of the buffers and the predominantly downslope orientation of falls.

Tree falls were triggered by another falling tree in about 30 percent of the surveyed cases. Thus, even though the width of the zone of direct influence to the channel is a distance approximately equal to a tree's height, the importance of secondary tree falls expands the width of buffer strip required to maintain the physical integrity of the channel. The distribution of input sources was thus recalculated to account for the influence of trigger-trees *(fig. 4)*.

Influences of tree fall on sediment inputs to the channel are of three types: direct input from sediment transport by uprooting, direct input from the impact of the falling tree on channel banks, and indirect input from modification of channel hydraulics by wood in the channel. At low to moderate rates of debris loading, sediment input from the latter source is expected to be proportional to the amount of woody debris introduced to the channel. Sediment input from root-throw depends strongly on the proximity of the tree-throw mound to the channel. In general, only those uprooted trees originally located within a few meters of the channel contributed sediment from rootwads. Observations after the 1995 storm suggest that 90 percent of the sediment introduced directly by tree fall in the un-reentered forested reaches originated from within 15 m of the channel, while in buffer strips, sediment was introduced by trees falling from considerably farther away *(fig. 5)*. Rates of direct sediment input by tree fall during the storm were on the order of 0.1 to 1 m^3 of sediment per kilometer of main-stem channel bank.

The second focus of the study was to describe the distribution of fall rates as a function of distance from a clearcut edge and to compare rates of fall in buffer strips and un-reentered forest. Total rates of woody debris input from buffer strips and un-reentered forests reflect both inherent differences in the likelihood of failure for individual trees and differences in the population of trees capable of contributing woody debris: selectively cut buffer strips have fewer trees available to fall. Failure rates thus were calculated as the average probability of failure for a living tree 15 cm in diameter or greater.

Rates of tree fall were expected to be high immediately adjacent to channels, where high flows and bank erosion might also destabilize trees. Tree-fall rates thus were calculated as a function of distance from the channel bank for both buffer strips and un-reentered forest. Results show no statistically significant increase in fall rate near the channel in either setting. Mortality rates on the

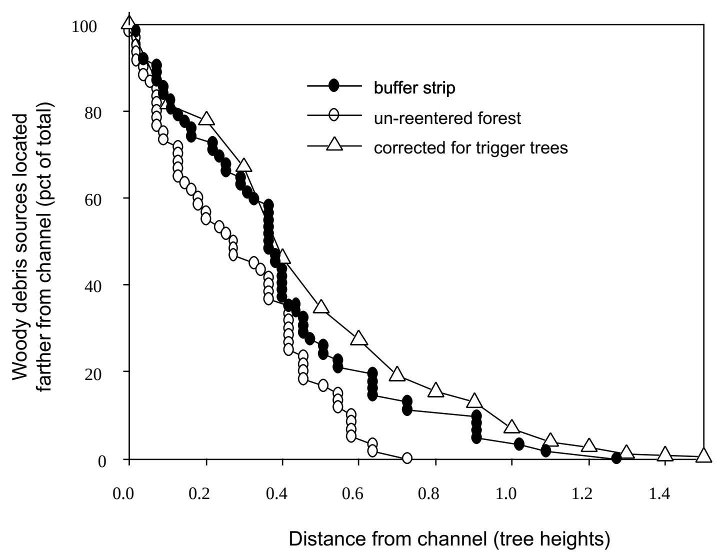

Figure 4—The distribution with respect to the channel edge of sources for woody debris inputs to North Fork Caspar Creek from buffer strips and un-reentered forest. The recalculated curve accounts for inputs from tree falls triggered by trees falling from farther upslope. An average canopy height of 55 m is assumed.

floodplain site are equivalent to those expected for other sites at similar distances from a clearcut edge.

Rates of tree fall were also expected to decrease as a function of distance from the outer edge of the buffer strip as the extent of exposure decreases. However, data indicate no clear pattern in fall distribution, and increased rates persist for the full widths of the buffer strips. In particular, excess fall rates do not consistently decrease through the width of the selectively cut portion of the buffer, suggesting that the fall rate may reflect the combined influence of the selective removal of trees and the presence of the newly exposed stand edge.

The distribution of fall rates within un-reentered stands was then examined to determine whether the influence of the clearcut boundary persisted even farther into the stands. In un-reentered stands (*fig. 6*, open symbols), average fall rates (R, percent downed per year) are correlated with the distance between the plot center and the nearest clearcut edge (x, meters):

$$R = 1.36e^{-0.00915x} \qquad r^2 = 0.66 \tag{1}$$

That the relationship exists suggests that, of the measured rates, the most appropriate estimate of a background fall rate is that of 0.12 percent per year measured in the most isolated control plot for the 6-year study period, or about 0.4 trees per hectare per year.

However, the trend of the relation shown in *figure 6* suggests that the background rate has not been fully achieved by 264 m into the stand, the distance represented by the most isolated of the study plots. The potential minimum background rate can be estimated using the assumption that the influence of a clearcut edge would not be felt beyond a ridge. Extrapolation of the relation to estimate the failure rate at a distance of 350 m from a clearcut edge (the maximum slope length for the watershed) provides an estimated minimum of 0.06 percent mortality per year for a completely un-reentered second-growth forest. The rate measured for the 264 m plot thus is no more than about twice the minimum possible rate, and the actual difference is likely to be considerably less. The measured value of 0.12 percent thus will be assumed to be representative of background fall rates in subsequent calculations.

In any case, tree falls were identified and counted consistently in each study plot, so tree falls in excess of the expected background rate can be attributed to the inherent spatial variability of rates and to the effects of logging. Assuming that spatial variability is randomly distributed, calculated excess tree falls for each plot can be divided by the number of years since logging to estimate the average annual rate of tree fall induced by nearby logging. Results for buffer strips (exclusive of the landslide and floodplain sites) show an average annual total fall rate (including both excess and background rates) of 1.9 ± 0.7 percent for the period since logging, or about 3 to 7 trees per hectare per year. Comparison of rates between buffer plots and the most isolated control plot suggests that the probability of failure for a tree in a buffer strip is approximately an order of magnitude higher than that for trees in the un-reentered second-growth redwood forest.

Equation (1) provides an expected annual fall rate of 1.1 percent for the average distance-to-edge of 21 m for the buffer-strip plots. The expected average rate is about 60 percent of the measured average, again suggesting that proximity to the boundary may not be the only factor influencing the fall rates in the selectively-cut buffer strips. It is possible, for example, that opening of the buffer-strip stand by selective logging may also contribute to

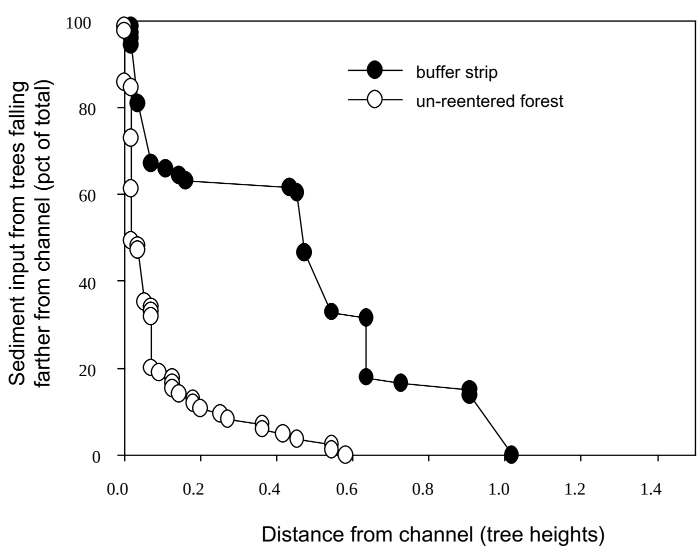

Figure 5—The distribution with respect to the channel edge of tree falls associated with sediment production to North Fork Caspar Creek from buffer strips and un-reentered forest. Sources are weighted by the approximate volume of sediment contributed. An average canopy height of 55 m is assumed.

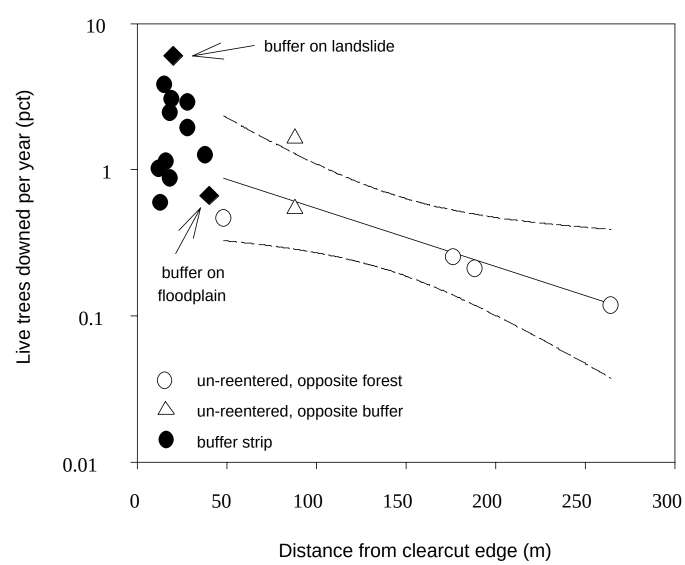

Figure 6—Probability of failure of live trees as a function of the distance between the center of each study plot and the edge of the nearest clearcut. The regression line and 95 percent confidence band are calculated for un-reentered plots (open symbols); data from buffer-strip plots are not included in the regression.

destabilization of the remaining trees.

Rates of tree fall are expected to stabilize with time after logging. Weidman (1920), for example, reports that two-thirds of the excess tree fall in selectively logged western yellow pine stands occurs within 5 years of logging, and Steinblums and others (1984) note that most excess tree fall in 40 buffer strips of the Oregon Cascades occurred during the first few years. For Caspar Creek, data from the long-channel survey allow calculation of rates of failure during a single storm that occurred 4 to 6 years after clearcutting. By this time stands had already been partially depleted of unstable trees, and remaining trees had had an opportunity to increase their wind-firmness through modification of foliage and rooting patterns. Overall instances of woody-debris input per unit length of channel during the storm generally increase slightly upstream, and rates of input were similar along uncut and buffered reaches. However, stand density at the time of the storm was significantly lower along the buffered reaches, and the probability of failure for an individual tree remains higher in buffer zones even after 4 to 6 years after cutting when stand density *(fig. 7)* and long-channel location *(fig. 8)* are accounted for. This pattern suggests that the disparity in stocking rates between buffer strips and un-reentered forests is continuing to increase.

Data from the post-storm survey also indicate that in-fall frequencies from the north bank were generally lower than those from the south bank. The pronounced tendency of trees on both north- and south-facing slopes to fall downslope suggests that the larger angle between buttressing roots and bole may provide less resistance to failure in a downslope direction. Failure may thus be most likely when strong winds blow downslope. In addition, any north-side trees that did fall in the direction of the major southerly storm winds would fall away from the channel and thus not be included in the post-storm survey.

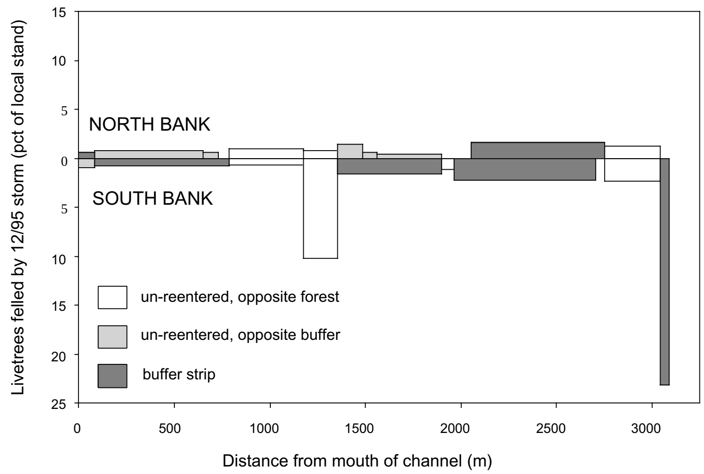

Figure 7—Distribution of tree falls along North Fork Caspar Creek during the storm of December 1995 in terms of probability of failure for a live tree. High rates at 1300 m and 3050 m represent localized concentrations of very intense blowdown, possibly reflecting the influence of localized wind eddies.

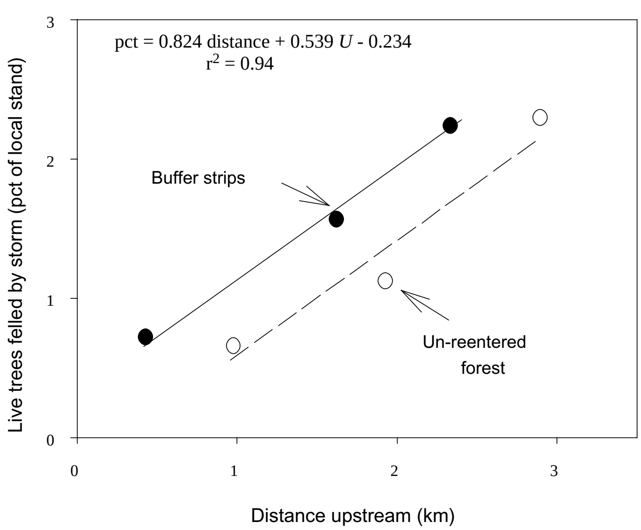

Figure 8—Tree-fall rates from the December 1995 storm in buffer strips and un-reentered forest stands along the south bank of North Fork Caspar Creek. Data from localized areas of extreme blowdown and from uncut forests opposite buffer strips are not included. The dummy variable, U, takes on a value of 0 for un-reentered forest and 1 for buffer strips.

In general, then, results suggest that the presence of a clearcut can at least double tree-fall rates for a distance of more than 150 m into a stand composed of 50- to 60-m-high second-growth trees *(fig. 6)*. These results are consistent with results reported by Chen and others (1995), which show that wind speeds remain higher than expected for a distance of 240 m in from the edge of stands of 50- to 65-m-tall old-growth Douglas-fir forests in Washington and Oregon. The effect might be expected to be even stronger where a portion of the remaining stand has been selectively logged, as in the Caspar Creek case.

Conclusions

Results suggest that the strategy used for buffer-strip design along North Fork Caspar Creek produces an order-of-magnitude increase in the probability of failure for individual trees during the first 6 years after logging, and that a more modest increase in fall rate persists beyond 6 years. Failure rates throughout the width of the selectively logged portion of the buffers remain higher than predicted on the basis of proximity to the edge, suggesting that the increased rates in that portion may reflect both selective logging and the presence of a clearcut edge. In any case, the 30-m-wide selective cut does not protect the innermost 15 m of uncut buffer from accelerated rates of fall.

Results also suggest the need to expand the conceptual basis for defining a "core buffer" with a natural distribution of tree species and sizes, as required to sustain the physical integrity of the stream channel. Although 96 percent of the in-falling wood is derived from within one tree-height's distance of the channel, about 30 percent of these falls resulted from trees being hit by another falling tree. Because the triggering trees could have been located at even greater distances from the channel, this pattern indicates that an additional increment of width is required to sustain the appropriate fall rate of potential trigger trees. If this additional width is not considered during the design of a fringe buffer, accelerated fall rates of marginal trigger trees would increase rates of secondary tree fall within the core zone.

How wide a buffer is wide enough? In this case, preliminary results suggest that a one-tree-height width of uncut forest that is allowed to sustain appropriate fall rates would include 96 percent of the potential woody debris sources for the channel system. Combining the pattern of source trees with the distribution of triggering tree-fall distances indicates that an additional 0.1-tree-height's width would be needed to preserve the fall rate of trigger-trees that is needed to sustain the 96 percent input rate *(fig. 4)*. Beyond this, an uncut fringe-zone of 3 to 4 tree-height's width would be necessary to ensure that the fall rate within the core zone is within a factor of 2 of background rates *(fig. 6)*. Thus, a total no-cut zone of at least 4 to 5 tree-heights' width would appear to be necessary if woody debris inputs are to be maintained at rates similar to those for undisturbed forested channels. Such provisions might be necessary also along property boundaries if neighboring landowners are to be protected from excessive wind damage.

However, the utility of the fringe zone is highest during the years immediately after logging because fall rates will eventually decrease as neighboring stands regrow, as marginal trees become more wind-firm, and as the most susceptible trees topple. If the early increase in fall rates attenuates rapidly and growth rates within the depleted stand increase because of the "thinning," the long-term influence of the pulse of tree fall may be relatively small. Longer-term monitoring of fall rates and stand development is necessary if the long-term significance of accelerated fall rates—and thus the level of protection needed from a fringe buffer zone—is to be assessed adequately.

At this point, results of the study are preliminary, and they reflect conditions in a single watershed. Relationships such as that shown in *figure 6* will need to be tested in other areas. Sites will also need to be monitored over a longer period. Because the partially cut buffers and nearby uncut stands now have significantly fewer standing trees than the more remote un-reentered stands, it is likely that the disturbed stands will eventually start producing less woody debris. Additional information concerning debris mobility, decay rates, stand development, and stand-age-dependent mortality could be used to model future changes in debris input, allowing assessment of future influences on channel processes.

This study's results are based on measurements made in a 50- to 60-m-tall, second-growth redwood forest. Not only do these sites not reflect the canopy height in which the local stream ecosystems developed, but they do not reflect the background rates or characteristics of tree fall appropriate for the setting. Under natural conditions, woody debris inputs would have included pieces far larger and more decay-resistant than the current stand is capable of producing. Additional information about debris input and decay rates in natural settings could be used to compare predicted future debris regimes in the recovering system with those appropriate for the natural system in the area.

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