Sensitivity of a Riparian Large Woody Debris Recruitment Model to the Number of Contributing Banks and Tree Fall Pattern

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ABSTRACT: *Riparian large woody debris (LWD) recruitment simulations have traditionally applied a random angle of tree fall from two well-forested stream banks. We used a riparian LWD recruitment model (*CWD*, version 1.4) to test the validity of these assumptions. Both the number of contributing forest banks and predominant tree fall direction significantly influenced simulated riparian LWD delivery, but there was no apparent interaction between these factors. Pooled across all treatments, the average predicted 300-year cumulative LWD recruitment was 77.1 m^3/100 m reach with both banks forested compared to 49.3 m^3/100 m reach when only one side was timbered. Total recruitment within bank cover categories (one versus both forested) depended on the directionality of the falling stem. When only one bank was forested, the* CWD *model predicted the same riparian LWD recruitment for the random and* CWD *default tree fall patterns (~39 m^3/100 m reach), the pattern biased toward the channel yielded twice this volume, a pattern quartering toward the channel produced 64% more LWD, and the pattern paralleling the channel contributed almost 30% less than random. With both banks forested, the random, default, and quartering simulations resulted in similar delivery (about 78 m^3/100 m reach), the pattern biased toward the channel contributed almost 14% more LWD, and the parallel pattern yielded 26% less. Because* CWD *is similar in design and operation to other riparian LWD recruitment models, it follows that any simulation of wood delivery to streams should be checked for their consistency with local forest cover and tree failure patterns.*
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Key Words: LWD, *CWD*, FVS, riparian zone management.

Large woody debris (LWD) recruitment is a critical process in healthy riparian ecosystems (Bisson et al. 1987, Dolloff 1994, Kershner 1997). The recovery of historical wood loads is often a primary goal of streamside management (Berg 1995, Kershner 1997), especially for channel process restoration and fish habitat improvement in western North America. Research on riparian LWD has concentrated on its ecological function, with a growing body of work on recruitment mechanisms (e.g., McDade et al. 1990, Robison and Beschta 1990, Grizzel and Wolff 1998, Hairston-Strang and Adams 1998, Benda et al. 2002). Synchronous with the evolution of new technological and regulatory environments, interest has also risen in computer modeling of riparian LWD recruitment as a means to evaluate riparian forest management. To this end, numerous simulation models have been developed in recent years (e.g., Rainville et al. 1985, Van Sickle and Gregory 1990, Beechie et al. 2000, Bragg et al. 2000, Welty et al. 2002).

Key to any investigation of natural phenomena using computer simulation is knowing how model assumptions and design influence predictions. Riparian LWD delivery models implicitly or explicitly incorporate factors like tree proximity, lean and direction, the degree and evenness of forest cover, and wood recruitment pathways. Simulations have examined factors like source distance (e.g., McDade et al. 1990, Welty et al. 2002), tree lean (e.g., Hairston-Strang and Adams 1998), and delivery mechanism (e.g., Benda et

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al. 2002), but primarily with models developed for mesic, well-forested regions like the Pacific Northwest. Transference of these designs may be problematic if assumptions suitable for simulating channel LWD delivery are inappropriate for other systems. For example, the influence of the number of contributing banks and forest cover on riparian LWD recruitment dynamics in the Pacific Northwest may differ appreciably from the central Rocky Mountains (Figure 1).

Furthermore, model users have often assumed random tree fall without testing the validity of this premise. Random tree fall directions can occur in forests when failure is not influenced by either disturbances or geomorphology (e.g., slope, exposure) (Maser and Trappe 1984, Robison and Beschta 1990, Van Sickle and Gregory 1990), though other distinct patterns are possible and perhaps even likely. Examples like the tri-modal distribution found by Bragg et al. (2000) and unidirectional tree fall patterns related to predominant wind direction or slope have been reported (e.g., Alexander and Buell 1955, Schmid et al. 1985, Grizzel and Wolff 1998).

Many riparian LWD recruitment models can be manipulated to vary the degree of forest cover and consider nonrandom tree fall patterns (e.g., Robison and Beschta 1990, Van Sickle and Gregory 1990, Bragg et al. 2000, Benda et al. 2002). We decided to test the number of contributing banks and angle-of-tree-fall pattern on riparian LWD delivery using the *CWD* model (Bragg et al. 2000). In particular, we were interested in the following questions. First, does the number of contributing banks significantly affect simulated riparian LWD recruitment? Second, what is the predicted impact of tree direction-of-fall pattern on channel wood delivery, and does it interact with bank forest cover? Finally, what are the implications of these simulated results on the application of riparian LWD recruitment models? Addressing these issues should improve the prediction of riparian LWD delivery and, consequently, the development and implementation of streamside management strategies.

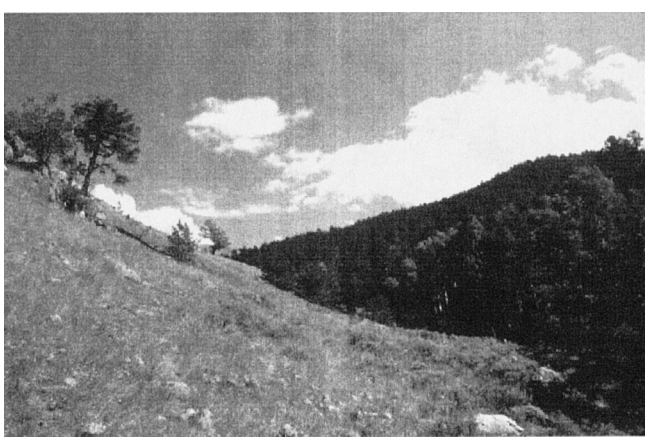

Figure 1. Dramatic differences in bank cover from a drainage in NW Wyoming where aspect plays a considerable role in determining forest cover (photograph by D.C. Bragg).

Methods

Design and Assumptions

The riparian LWD recruitment simulator *CWD* (version 1.4) was used to predict bankfull channel delivery. *CWD* is a postprocessor to the Teton and Utah variants of the Forest Vegetation Simulator (*FVS*, version 6.1) (Wykoff et al. 1982). While a detailed discussion of all *FVS* and *CWD* interactions is beyond the scope of this article (see Bragg et al. 2000 for model assumptions), we will briefly describe the most relevant features. *FVS* is solely responsible for the inception, growth, and death (both disturbance- and self-thinning-based) of simulated trees. *CWD* extracts the trees identified as dead by *FVS*, locates them within the riparian zone, selects an angle-of-fall, fells and breaks the tree, and assigns which pieces are recruited to the bankfull channel (Figure 2). *CWD* also allows the user to define riparian

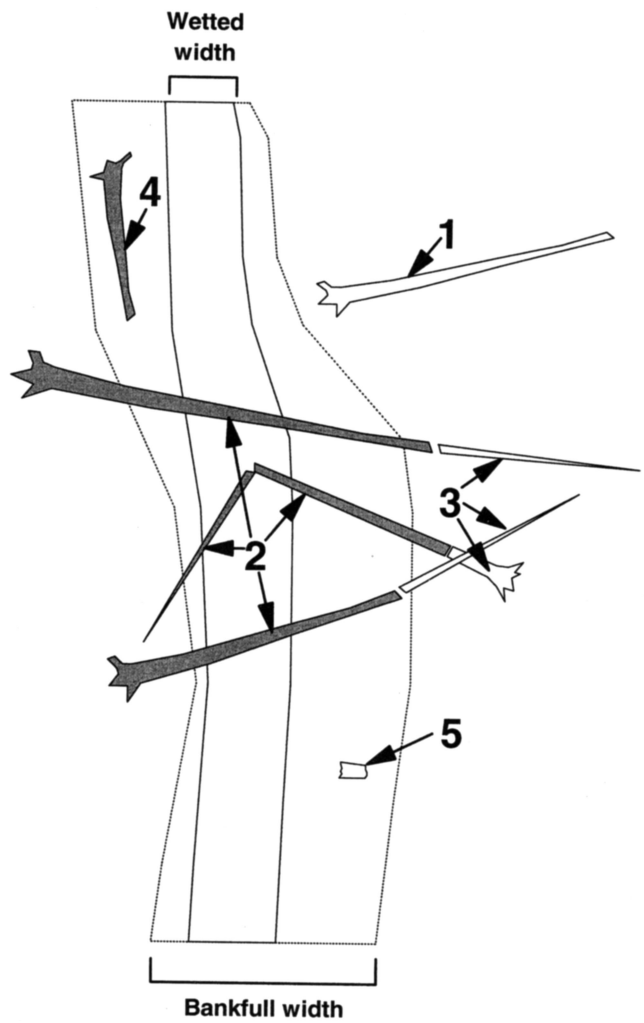

Figure 2. Categorization of recruited riparian LWD based on position to the bankfull channel. Pieces of debris that fall away (1) from the channel are easily excluded, while those reach the channel are usually considered delivered (2). Some pieces break off on the near or far bank (3) and if they do not sufficiently extend into the bankfull channel, they were not tallied. However, debris does not have to contact the wetted zone to be recruited, so long as it sufficiently extends into the bankfull width zone (4). All pieces must meet minimum size requirements (5).

LWD dimensions (assumed for this study to be dead wood at least 10 cm in diameter and a minimum of 1 m long). LWD was considered "recruited" to the bankfull channel if it extended at least 1 m into this zone (Figure 2). *CWD* distributes snag locations relative to the bankfull channel following a predetermined distribution and can allocate the simulated trees to one or two banks, permitting stands of varying density or composition. Because it is solely a recruitment model, *CWD* does not directly monitor in-channel wood depletion.

It is in the delivery process that *CWD* allows for the testing of bank cover and tree angle-of-fall patterns on riparian LWD recruitment. With two forested banks, debris can be delivered from both sides of the channel. This contrasts with streams with only one bank forested, where there are no trees on the opposite bank to produce downed wood. *CWD* divides angle-of-fall into nine 20° categories ranging from 0° (directly toward the channel) to 180° (directly away from the channel). In *CWD*, the angle-of-fall pattern set by the user is fixed for the whole riparian forest (not just a particular bank), so biased fall directions must be carefully designed to capture the pattern most consistent with local conditions. Figure 3 illustrates the probability of LWD recruitment generated under one of five different tree fall patterns: (1) random directions; (2) tri-modal (*CWD* default); (3) trees falling primarily toward the channel (TWRD); (4) a design quartering toward the channel (QRT); and (5) a tree fall pattern largely paralleling the channel (PRL) under two different contributing bank conditions (one [O] or both [B] banks forested). The *CWD* default scenario was adapted after field sampling small streams in the Bridger-Teton National Forest of northwestern Wyoming (Bragg et al. 2000), and all others are simplified examples of key patterns.

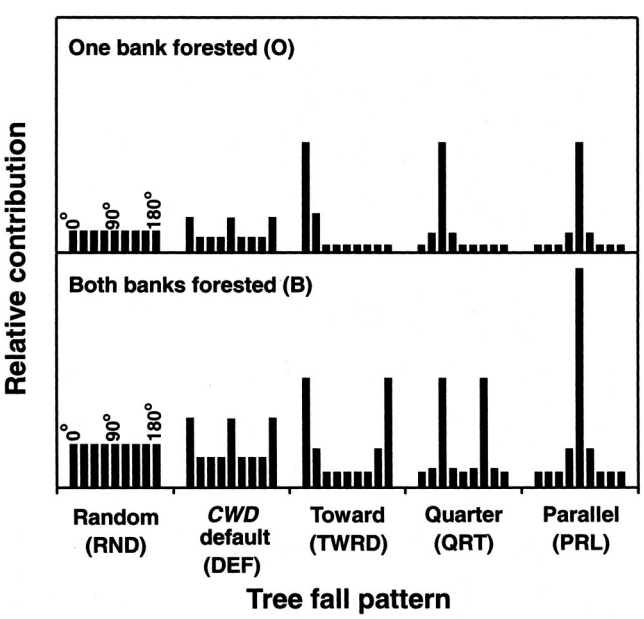

Figure 3. Modeled tree failure trends by bank cover and tree fall pattern. Each bar represents a 20° angle-of-fall class ranging from 0° (directly pointing at the stream) to 180° (opposite direction of the stream). See text for further description of modeled scenarios.

Modeled Stream Description

Dry Lake Creek, a second-order stream ~60 km NE of Jackson, WY was used for these simulations. Along a 300-m sample reach, Dry Lake Creek had a mean bankfull width of 5.5 m, an average gradient of 3.5%, a mean elevation of 2,565 m, and drained an upstream basin of 1,033 ha (Bragg et al. 2000). Six 0.1-ha circular plots were established 20 m from the bankfull channel (three on each bank), and all trees ≥10 cm dbh were identified to species and had their diameters recorded. The sampled streamside forest averaged 33.2 m^2/ha of live basal area, predominantly in Engelmann spruce (*Picea engelmannii*) (56% of stems) and subalpine fir (*Abies lasiocarpa*) (28%), with lesser amounts of lodgepole pine (*Pinus contorta*) (14%), blue spruce (*Picea pungens*) and limber pine (*Pinus flexilis*) (both <2% of stocking). Riparian bankfull LWD volume along this reach of Dry Lake Creek averaged 8.6 m^3/100 m (Bragg et al. 2000).

Both banks along of this particular stream reach were heavily wooded, but for demonstration purposes, half of the simulations were run with only one side forested. An average bankfull width of 5.5 m and a streamside forest depth of 38 m for each bank were assumed. All model runs encompassed a 300-year simulation period because previous work in riparian spruce-fir forests of the central Rocky Mountains had suggested that most long-term vegetation, natural disturbance, and channel LWD recovery dynamics would be captured, including autogenic processes like forest succession (Romme 1982, Bragg 2000).

Statistical Design and Analysis

Because this article considers the impact of tree fall and bank cover on modeled riparian LWD recruitment, it was determined that only one stream was necessary to highlight the sensitivity of *CWD* and similar recruitment models to variation in these key assumptions. Actual recruitment patterns depend on the composition, age, and structure of streamside forests, bankfull channel width, prevailing wind direction, management practices, and other factors.

To address the limited stochasticity of some *CWD* subroutines, 10 replicates were run for each scenario. Cumulative LWD recruitment (in m^3/100 m reach) over the simulation period was compared to determine the impact of the number of contributing banks and tree fall patterns. Initial analysis found significant heterogeneity of variance and non-normal data distributions, neither of which responded to log transformations. Therefore, a nonparametric two-factor extension of the Kruskal-Wallis analysis of variance (ANOVA) test and a corresponding nonparametric multiple comparison using rank scores were used to identify treatment effects (Zar 1984). The nonparameteric mean separation test is more conservative than its parameteric analog, but is not as sensitive to normality and variance heterogeneity assumptions.

Table 1. Nonparametric two-factor analysis of variance results for the hypotheses of bank cover, tree fall pattern, and interaction effects.

Factor	*SS*	*df*	H^a	$\chi^2_{0.05,df}$	Conclusion
Cells	76178.5	9	—	—	—
Bank cover[b] (H_0 = no effect of bank cover)	36672.3	1	43.5710	3.841	reject H_0
Tree fall (H_0 = no effect of tree fall pattern)	35120.9	4	41.7278	9.488	reject H_0
Bank cover × fall pattern (H_0 = no interaction between bank cover and tree fall pattern)	4385.3	4	5.2102	9.488	accept H_0

[a] Test statistic H = factor *SS*/total *MS*. If $H < \chi^2$ statistic (at $\alpha = 0.05$ and corresponding degrees of freedom), then we failed to reject the null hypothesis (Zar 1984).

[b] Bank coverage compares the number of contributing banks (one vs two).

Results

Both bank cover and tree fall patterns significantly ($P < 0.05$) affected cumulative LWD recruitment to Dry Lake Creek, but there was no interaction between these factors (Table 1). The number of contributing banks consistently influenced the role of tree angle-of-fall, with LWD recruitment always lower from streams with one forested bank. When all fall patterns were averaged across bank forest cover, having both banks forested was predicted to deliver 77.1 m^3/100 m reach (standard deviation (SD) = 11.41), while the mean for one bank forested was 49.3 m^3/100 m reach (SD = 20.27). With only one bank forested, random (ORND), default (ODEF), and parallel (OPRL) tree failure patterns (Figure 4) produced approximately 50% less LWD recruitment for the same fall patterns than when both banks were forested (BRND, BDEF, and BPRL). Of these treatments (Table 2), only the BPRL versus OPRL comparison did not prove statistically significant ($P > 0.10$). For OTWRD and OQRT, cumulative recruitment declined 15–20% from BTWRD and BQRT, neither of which was statistically significant. The apparent insignificance of some relatively large recruitment differences arose from the more conservative nonparametric test used to evaluate the differences. However, the consistent trend of lower LWD delivery when only one bank was forested resulted in the rejection of the null hypothesis that there was no effect of the number of contributing banks on predicted cumulative recruitment.

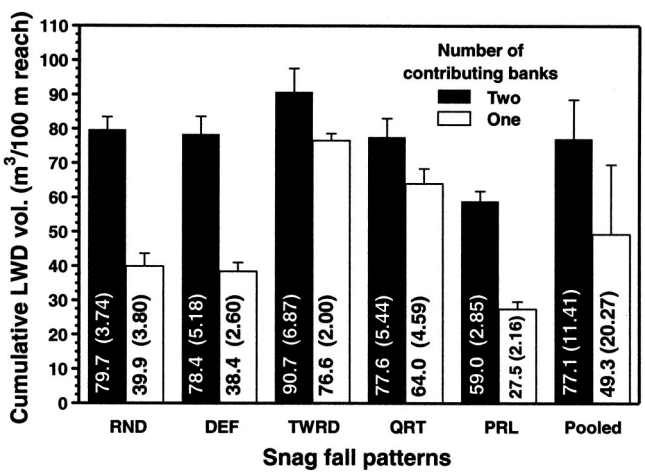

Figure 4. Predicted 300-year cumulative LWD recruitment under different levels of bank forest cover (one versus two contributing banks). Volumetric values represent treatment means and standard deviations (in parentheses).

This study also found within-bank cover differences in cumulative LWD delivery (Table 2). The pattern with tree fall biased predominantly toward the channel (TWRD) produced the greatest recruitment regardless of the number of contributing banks, while the pattern predominantly paralleling the channel (PRL) yielded the least woody debris. While BTWRD did not prove significantly different from BQRT, BDEF, and BRND, it was significantly higher than

Table 2. Statistical differences between all treatments, tested nonparametrically using multiple comparisons of ranks (Zar 1984). Differences in the absolute value of the pairs of ranked cumulative recruitment scores (unitless) are to the top and right of the table, while the calculated *q* values[a] and their significance[b] are to the bottom and left of the table.

	BRND	BDEF	BTWRD	BQRT	BPRL	ORND	ODEF	OTWRD	OQRT	OPRL
BRND		34.5	167.0	34.5	398.0	547.0	573.0	110.5	317.0	710.0
BDEF	0.3761		201.5	42.5	363.5	512.5	538.5	76.0	282.5	675.5
BTWRD	1.8203	2.1964		244.0	565.0	714.0	740.0	277.5	484.0	877.0
BQRT	0.3761	0.4633	2.6596		321.0	470.0	496.0	33.5	240.0	633.0
BPRL	4.3382*	3.9622	6.1585**	3.4989		149.0	175.0	287.5	81.0	312.0
ORND	5.9623**	5.5863**	7.7826**	5.1230**	1.6241		26.0	436.5	230.0	163.0
ODEF	6.2457**	5.8697**	8.0660**	5.4064**	1.9075	0.2834		462.5	256.0	137.0
OTWRD	1.2045	0.8284	3.0248	0.3652	3.1338	4.7579**	5.0413**		206.5	599.5
OQRT	3.4553	3.0793	5.2756**	2.6160	0.8829	2.5070	2.7904	2.2509		393.0
OPRL	7.7390**	7.3630**	9.5593**	6.8997**	3.4008	1.7767	1.4933	6.5346**	4.2837*	

[a] Calculated q = Difference/*SE*, where: $SE = \sqrt{n(nk)(nk+1)/12}$, ($n = 10$, $k = 10$).

[b] * = significant at $0.05 \le P < 0.10$; and ** = significant at $P < 0.05$, determined by using the following test statistics: $q_{0.10,\infty,10} = 4.129$ and $q_{0.05,\infty,10} = 4.474$.

BPRL. BTWRD ($P < 0.05$) and BRND ($P < 0.10$) were also noticeably more likely to contribute LWD to the channel than BPRL. When only one bank was forested, OTWRD recruited significantly more LWD than OPRL, ODEF, and ORND (35%, 50%, and 52% of OTWRD's cumulative total, respectively). Additionally, OQRT provided significantly ($P < 0.10$) more LWD to the channel than OPRL. The differences recorded between ORND, ODEF, and OPRL were not significant (Table 2).

Discussion

Even though the bank cover and tree fall patterns presented in this article are greatly simplified examples, the trends shown are ecologically meaningful. Coupled with distance to the channel, the number of contributing banks and tree fall patterns are major determinants affecting riparian LWD recruitment (McDade et al. 1990, Robison and Beschta 1990, Van Sickle and Gregory 1990). This conclusion was anticipated by Van Sickle and Gregory (1990), who predicted that trees falling from an equally dense streamside forest directly toward the channel would yield up to three times that of purely random patterns. Another potential biasing factor, tree lean, does not play as obvious a role in riparian LWD delivery as wind direction. Hairston-Strang and Adams (1998) discounted the impact of tree lean on overall recruitment, stating that trees falling in the direction of their lean would have contributed a statistically insignificant increase of 2–7% from a random fall pattern.

Given the scenarios tested for this article, having both banks forested ameliorated the impact of biased fall patterns (Figure 4) because *CWD* assumed that the events leading to tree fall are equally likely on both banks. Some directional patterns did produce more (or less) LWD recruitment (e.g., BTWRD and BPRL), but the 300-year cumulative delivery for all scenarios was consistently substantive (>50 m^3/100 m reach). When both banks are forested, a unimodal pattern away from the channel on one bank translates into a unimodal trend toward the channel on the other side. This scenario differs from the steep riparian forests described by Robison and Beschta (1990) and Van Sickle and Gregory (1990), where downslope toppling was thought to be important. Under this condition, failure patterns for both banks are concentrated toward the channel, greatly increasing riparian LWD recruitment (Van Sickle and Gregory 1990).

When only one bank was forested, both the magnitude and the absolute volume of LWD recruited were substantially lower than when both banks were wooded (Figure 4). With the exceptions of OTWRD and OQRT, cumulative LWD delivered from one forested bank is considerably less than that provided by any scenario for well-forested channels. Three of the simulated patterns (ORND, ODEF, and OPRL) yielded ~50% less debris than their counterparts when both banks were forested. Rather than uniformly decreasing by half the LWD recruitment totals, the biased patterns tending toward the channel (OTWRD and OQRT) decreased only 15–20% of the totals from BTWRD and BQRT. This suggests that trees falling along a major axis are the most important component of long-term LWD recruitment, and can offset much of what would be expected under a random failure pattern. Note that the 20° predominant fall category used by *CWD*, coupled with the contribution from adjacent classes, more than offset the LWD recruitment from a random pattern. Conversely, if the tree fall pattern is predominantly away from the channel in a one-bank scenario, then recruitment will be considerably less.

The simulated example (completely forested versus only one bank forested) presents an extreme case of the impact of bank stocking on recruitment levels. Even a gradient of forest cover could noticeably affect riparian LWD recruitment, especially if the differences in tree density or size were large. When modeling riparian LWD recruitment of a specific reach, one should not simply assume random tree fall from equally well-forested banks. Under the scenarios tested, we found the angle of tree failure can result in long-term variation from about −30% to upwards of 100% more debris than would be derived from a purely random pattern. This case study using the *CWD* model is a cautionary tale for other simulation-based studies of riparian LWD recruitment. Because most other wood delivery models apply similar designs, they also may be subject to significant departures if inappropriate tree fall pattern(s) and bank coverage assumptions are applied.

The results of this study also have implications for adaptive riparian zone management. First, the interaction between downed logs and streams partially depends on the directional nature of the recruitment event(s) responsible for their delivery, especially for small, low-energy streams with limited ability to redistribute large pieces. If managed systems appear incapable of matching input patterns observed in undisturbed streams of similar size, gradient, flow, LWD orientation, and bank cover, then changes may be warranted if the goal is to better emulate unmanaged systems. Second, tree angle-of-fall may be indicative of important large-scale pattern and process occurring along the riparian zone. For example, tree fall directional patterns have been associated with predominant disturbance regimes (e.g., Veblen 1986). Because processes like natural catastrophic disturbance are now seen as important and perhaps even desirable (Dale et al. 2000), then restoration efforts should be compatible with these events. Finally, if harvesting near LWD recruitment zones, observe the changes in tree fall direction resulting from past logging of similar portions of the landscape. The alteration of forest structure may noticeably change local failure patterns due to increased debris flows or wind turbulence around stand edges. Retaining more forest cover along upwind contributing banks should more effectively maintain LWD recruitment than a design that treats all sides equally.

Conclusions

As computer models become commonplace tools of field managers, a better understanding of their assumptions is warranted. This includes testing their sensitivity to patterns that differ from the traditional examples used to illustrate model capability. After all, the real world contains a degree

of variability that makes it difficult for many practitioners to feel comfortable with a simulation model, especially if it cannot emulate familiar conditions.

A number of studies have shown the importance of tree proximity to the channel on overall recruitment (McDade et al. 1990, Robison and Beschta 1990, Van Sickle and Gregory 1990), but this is only one of several factors contributing to riparian LWD delivery (Hairston-Strang and Adams 1998). This article considered the response of a riparian LWD recruitment model to notable departures from the well-forested, random tree fall direction situations frequently portrayed. The number of contributing banks and tree angle-of-fall significantly influenced riparian LWD recruitment. While these responses were expected, virtually no published simulation studies have addressed streamside forest coverage and tree fall when predicting long-term woody debris dynamics.

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