

AN ABSTRACT OF THE THESIS OF

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Title: Fall Directions and Breakage of Riparian Trees along Streams in the Pacific Northwest

Abstract approved:

Stanley V. Gregory

In the Pacific Northwest, regulatory agencies have recently implemented management strategies for restoration and maintenance of wood recruitment to streams over time. This allochthonous organic material is a critical component in the geomorphic and biological structure of forested streams. Mathematical models are commonly used to evaluate long-term wood dynamics in stream ecosystems. Accuracy and applicability of these models in a wide range of forest, geomorphic and regional conditions are limited by current understanding of tree fall patterns. I quantified fall directions and breakage of riparian trees at 21 second- to fourth-order stream sites in the Pacific Northwest, USA. These patterns influence rates, amounts and spatial distribution of wood delivered to streams.

Riparian tree fall directions strongly differed by species, rooting position away from the stream and side slope steepness adjacent to the channel.

Though average tree fall directions oriented towards stream regardless species, rooting position, and side slope, variance of fall directions significantly declined between valley bottoms and hillslopes and between gentle and steep side slopes. Standard deviation of fall directions, as calculated from circular statistical techniques, was two times greater on gentle slopes (0-10% steepness) than on extremely steep slopes (> 90% steepness) ($\pm 80^\circ$ versus $\pm 40^\circ$). A similar pattern occurred based on rooting position away from the stream (valley bottom versus hillslopes). Valley constraint, forest structure, forest age and region (west of the Cascades Mountains crest versus the Interior Columbia Basin) were not associated with variation in fall directions ($p > 0.10$ in all cases). Several sites with relatively thin trees (height/dbh > 50 m/m) had overall upstream fall directions.

Over half (58%) of the riparian trees measured in this study did not break when they fell. Of riparian trees that were broken, 62% of breaks could not be attributed to physical features of the stream or riparian zone. Percent of trees with breaks slightly increased with forest age ($p = 0.08$). More significantly, percent of trees with fall breaks increased with tree height ($p < 0.0001$). Models indicated slight differences among species except for western larch (*Larix occidentalis* Nutt.), which had a significantly higher rate of breakage than other species. Trees that broke when they fell typically produced 2 to 3 pieces (geometric mean of 2.7 pieces with 42% coefficient of variation) and the first break typically occurred at half height (average of 0.50

with ± 0.24 standard deviation; proportion of height from base to top).

Effects of species type were insignificant on pieces produced or location of first break.

These results have several important implications for riparian zone management of forested streams in the Pacific Northwest. Topographic influences on tree growth patterns and rooting conditions could affect stream wood loading rates and patterns where riparian forest dynamics dominate input pathways. Stream sections with side slopes $> 90^\circ$ on both banks potentially receive 1.5 times more falling trees (by numbers) than sections with slopes 0-10% and 2.5 times more than what is expected from a random fall pattern. Breakage by falling trees on impact needs to be considered in simulations of wood recruitment from riparian forests. Large channel-spanning wood pieces that have potential to form pools and jams also have the highest probability to break when initially falling into the channel. A simple model of wood recruitment based on field data and riparian forest dynamics of an old-growth forest in the West Cascades of Oregon indicated that fall breakage might reduce numbers of channel spanning wood pieces entering a 10-m wide stream by 7 to 79% over a 100-year time period. At the same time, breakage may amplify absolute number of wood pieces entering a stream channel by 1.1 to 1.8 times. Overall, results presented in this thesis may improve accuracy and calibration of stream wood recruitment models for use in riparian management in the Pacific Northwest.

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Fall Directions and Breakage of Riparian Trees along Streams in the
Pacific Northwest

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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CONTRIBUTION OF AUTHORS

Drs. Stan Gregory and John Van Sickle contributed to the interpretation of data and content of both Chapters 2 and 3.

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FALL DIRECTIONS AND BREAKAGE OF RIPAIRAN TREES ALONG
STREAMS IN THE PACIFIC NORTHWEST

INTRODUCTION

Daniel J. Sobota

Stream ecosystems in forested landscapes are fundamentally linked to terrestrial vegetation dynamics (Vannote et al. 1980; Gregory et al. 1991). Allochthonous organic material originating from riparian vegetation provides the major metabolic energy base for many stream organisms (Minshall 1967; Fisher and Likens 1973). This material also enhances physical complexity and retentiveness of stream channels (Bilby and Likens 1980; Dolloff and Webster 2000). In the Pacific Northwest, wood is the most conspicuous form of allochthonous material entering forested streams (Bilby and Bisson 1999), comprising > 50% of organic matter in streams flowing through mature conifer forests (Allan 1995). Important functional roles of stream wood include providing stable habitat for fish (i.e., salmonids), aquatic macroinvertebrates and microbial communities (Benke and Wallace 1990; Tank et al. 1993; Roni and Quinn 2001), physically retaining fine inorganic sediments, organic matter and nutrients (Beschta 1979; Bilby and Ward 1989; Triska et al. 1989), and serving as a major energy and nutrient source (Ward and Aumen 1986; Sedell et al. 1988; Tank and Webster 1998; Bilby et al. 1999).

Amounts and distributions of wood in stream networks of the present day Pacific Northwest are significantly changed from conditions prior to Euro-American settlement (Sedell et al. 1988). Major rivers of have been cleared of snags to improve navigation and recreational safety conditions (Sedell et al. 1988; Bilby and Bisson 1999). Historical practices on small streams (< fifth-order; Strahler 1957) in the region have actively or indirectly removed great

quantities of wood from many drainage basins. Splash dams on small mountain streams were used in the nineteenth and early twentieth century for pulsed movement of harvested timber downstream; the practice effectively scoured wood and sediments from many headwater channels (Bisson et al. 1987). In recent times, stream-cleaning activities from the 1950s through the early 1980s attempted to increase fish habitat connectivity by removing wood from channels (Sedell et al. 1988; Bilby and Bisson 1999). Large-scale removal of wood from stream networks has been linked to simplification of channel structure (Hogan 1987), rapid mobilization of inorganic sediments from reaches (Beschta 1979) and reduced capacity of streams to sustain viable populations of resident and anadromous salmonids (Bryant 1983; Roni and Quinn 2001). Compounding these effects, land use activities such as timber harvest, agriculture and urbanization have extensively reduced abilities of riparian forests to act as a long-term source of wood to streams (Bilby and Bisson 1999; Beechie et al. 2000).

Recently, state and federal legislation in the Pacific Northwest have prioritized restoring and maintaining adequate amounts of wood in streams over time as an essential goal of riparian management zones along historically- and currently-forested streams (5-20 m bankfull width) (Oregon Department of Forestry 1994; Gregory 1997; Young 2000). General criteria for riparian management areas are implemented according to stream size, fish-bearing status and human use (specific guidelines vary among states and

federal agencies; see Gregory 1997 and Young 2000). Land managers have opportunities to evaluate site-specific dynamics and negotiate alternative management plans with enforcement agencies (e.g., Oregon Department of Forestry 1994).

A new application of mathematical models has been to evaluate effects of different forest harvest practices on delivery of wood to streams (Bragg et al. 2000; Beechie et al. 2000; Meleason 2001). These models are powerful tools for land managers interested in assessing site-specific wood recruitment potential because recruitment processes operate well beyond time scales of field studies (decades to centuries) (Bragg and Kershner 1997; Bragg 2000; Beechie et al. 2000; Meleason 2001). However, lack of empirical information on patterns and processes of recruitment currently limit accuracy and applicability of models across a wide range of forest, geomorphic and regional conditions.

In this thesis, I analyzed fall directions and breakage of riparian trees along second- to fourth-order forested streams. Sites were located in a diverse array of forest, geomorphic and physiographic settings in the Pacific Northwest. Tree fall directions and breakage strongly influences rates, amounts and spatial patterns of wood delivery to streams from riparian forests (Van Sickle and Gregory 1990; Meleason 2001). Existing field data on these two patterns are limited and inconsistent among studies. In Chapter 2, I quantify riparian tree fall directions and explore management implications with

a probabilistic model of tree fall into streams. Chapter 3 describes patterns of fall breakage along streams and analyzes variation in patterns on biological and physical gradients. Additionally, I investigate potential effects of fall breakage on abundance and length frequency distribution of wood entering streams.

Riparian tree fall directions along streams in the Pacific Northwest

ABSTRACT

We measured riparian tree fall directions along second- to fourth-order streams in the Pacific Northwest, USA, to evaluate patterns of wood recruitment to streams in a diverse array of environmental conditions. On average, riparian trees fell towards streams. Tree species, tree size, rooting position away from the channel and side slope steepness did not affect average fall directions of sampled populations of down riparian trees. However, standard deviation of tree fall directions, as calculated from circular statistical techniques, was two times greater on side slopes with 0-10% steepness compared to slopes > 90% steep ($\pm 80^\circ$ versus $\pm 40^\circ$). Valley constraint, forest structure (density, basal area and percent of basal area in hardwood species), forest age class (40-60, 80-150 and > 150 years old) and regional location (west of the Cascades Mountains crest or Interior Columbia Basin) were not associated with fall directions ($p > 0.10$ in all cases). Upstream tree fall directions were observed at three sites with trees that were thin relative to their height (tree height/dbh > 50 m/m). Our results indicate that stream sections with extremely steep slopes on both banks have the potential to receive 1.5 times more falling trees (by numbers) than sections with gentle slopes.

INTRODUCTION

Delivery of wood to streams is an important function of riparian zones in forested landscapes (Gregory et al. 1991). Wood serves as a stable habitat for aquatic organisms (Bilby and Bisson 1999), retards movement of inorganic and organic materials downstream (Beschta 1979; Bilby and Likens 1980) and is a major source of organic matter and nutrients to stream biota (Ward and Aumen 1986; Bilby et al. 1999). Tree fall directionality partially determines numbers, volume and spatial distribution of wood entering streams over time (Van Sickle and Gregory 1990). Empirical models that incorporate riparian forest dynamics, tree height and fall directionality are commonly used to forecast wood delivery to streams (e.g., Van Sickle and Gregory 1990; Beechie et al. 2000; Bragg et al. 2000). Though models are powerful tools for evaluating relative impacts of forest harvest practices on future stream wood conditions (Bragg and Kershner 1997; Beechie et al. 2000; Meleason 2001), accuracy and applicability of these models across a broad range of environmental conditions are limited by current understanding of tree fall patterns in riparian forests.

Field studies indicate that ~70% of wood volume in small streams flowing through mature and old-growth forests in the Pacific Northwest originates from trees standing on high terraces and hillslopes within 30-50 m upslope of the channel (Lienkaemper and Swanson 1987; McDade et al. 1990). Regulations for riparian management areas are based, in part, on

numbers and volume of wood delivered from riparian forests to channels over time (e.g., Oregon Department of Forestry 1994). Thus, rigorous quantification of riparian tree fall directions and factors influencing fall patterns are critical for effective ecosystem management.

Early models of wood recruitment to streams lacked empirical data of tree fall directions and therefore assumed that trees have an equal chance to fall in any direction (e.g., Rainville et al. 1986; Van Sickle and Gregory 1990). Several recent models assumed that trees preferentially fall towards streams but also lacked or did not report strong empirical evidence (e.g., Minor 1997; Bragg et al. 2000). Based on an equal chance to fall in any direction (random fall), probability of tree fall into a stream asymptotically declines upslope away from the channel (McDade et al. 1990). Assuming trees fall directly towards streams, probability for stream recruitment is 100% up to one tree height away from the channel. Over similar time periods and assuming similar riparian forest structure, number of trees falling into a stream is three times less from a riparian forest with random fall compared to fall directly towards the channel (Van Sickle and Gregory 1990).

Several riparian tree characteristics and environmental factors may influence fall directions along channels: species type, tree size, rooting position away from the stream, forest structure and—in particular—side slope to the channel (Alexander and Buell 1955; Lienkaemper and Swanson 1987; Robison and Beschta 1990; Ott 1997). Inconsistencies and small spatial scales of previous studies limit applicability of these factors in management

practices. A major question is the influence of side slope on probability of tree fall towards streams (Van Sickle and Gregory 1990; Bustos-Letelier 1994). Based on undocumented surveys of stream reaches in the Cascades Mountains of Oregon, probability of tree fall towards streams was represented in a model as 1.3 times greater on hillslopes (17-70% side slope) than flat valley bottoms (Minor 1997). In contrast, random fall was measured along stream reaches in steep-sided mountain valleys in the Coast Range and west Cascades of Oregon and Washington (McDade et al. 1990; Van Sickle and Gregory 1990). Tree size and shape are other factors indicated to influence eventual fall direction. In a study of mature and old-growth forests of southeast Alaska, large trees that comprised the upper canopy of the stand oriented with dominant storm winds whereas smaller trees in the understory fell in random directions or downslope (Ott 1997). Effects of tree size on tree fall directions in riparian zones have not been directly measured.

We measured riparian tree fall directions along second- to fourth-order (Strahler 1957) streams located west of the Cascades Mountains crest and in the Interior Columbia Basin of the Northwest, USA. Though previous studies have used similar number of reaches (21 in this study) to quantify source distance of wood to streams (e.g., McDade et al. 1990), we expanded the spatial scale of sampling to include streams in a broad range of physiographic conditions (streams in Oregon, Washington, Idaho and Montana). Additionally, we directly measured fall directions of riparian trees—including those that did not enter the channel—unlike previous research that only have

quantified down trees touching channels or floodplains. We specifically tested hypotheses commonly assumed in stream wood recruitment models:

- (1) Riparian tree fall directions are random.
- (2) Riparian tree fall directions are not influenced by species, tree size, rooting position, geomorphology, forest structure or regional location.

SITE DESCRIPTIONS

Second- to fourth-order streams (Strahler 1957; 1:24 000 United States Geological Survey quadrangle maps) were surveyed from west of the Cascades Mountains crest (11 streams; hereafter referred to as WCC) and the Interior Columbia Basin (10 streams hereafter referred to as ICB) in the Pacific Northwest, USA (Table 1; Fig. 1). Streams were selected arbitrarily and thus with inherent bias based on availability of access from private timber companies and the USDA Forest Service. Locations of specific study sites on streams were selected randomly. Study sites were 200-to-300 m in stream length (= 20 channel widths) and 50 m upslope ground distance on one or both stream banks. The upslope boundary was selected because previous work has indicated > 95% of trees directly falling into streams originate within 50 m upslope of Pacific Northwest streams (McDade et al. 1990).

Stream elevations ranged from approximately 800 to 1300 m on the ICB sites (east slopes of Cascades, Intermountain and Northern Rockies) and 100 to 750 m on WCC sites. WCC sites were slightly larger and more tightly constrained than ICB sites (valley constraint = average valley width / average active channel width; Gregory et al. 1991) (Table 1). Average active channel widths ranged from 3.4 m to 12.8 m (summary of widths taken at 20-m intervals at each site); valley constraint ranged from 1.3 to 25.7 among sites (Table 1). Stream gradients for sites ranged from 1-13% (based on hand-held clinometer measurements of 100-m longitudinal sections). Average side slope to the channel ranged from 12 to 68% at individual sites (based on hand-held clinometer measurements in down tree surveys).

Riparian forest ages were identified from discussions with land managers and inspections of stand age maps (Table 2). For both regions, forest ages were divided into three classes: 40-60, 80-150 and >150 years old. The first two age classes represent common rotation periods of timber harvest activities (Franklin et al. 1997). We chose > 150 years old to represent multiple canopy layer development (mature to old-growth stands) (Oliver 1981). Sites in western Oregon and Washington were entirely in the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forest zone (Franklin and Dyrness 1973). Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco.), ponderosa pine (*Pinus ponderosa* Laws.) and white alder (*Alnus rhombifolia* Nutt.) dominated the riparian forest canopy at two sites on the east slopes of the Cascades Mountains in Washington. Lodgepole pine (*Pinus contorta*

Dougl.), western larch (*Larix occidentalis* Nutt.), grand fir (*Abies grandis* (Dougl.) Lindl) and western redcedar (*Thuja plicata* Donn ex D. Don) comprised riparian stands in northeastern Oregon, central Idaho and northwestern Montana. We determined that stands in the 40-60 years old age classes originated following logging operations (with the exception of Piper Creek, MT) while those in older age classes probably regenerated after stand-clearing fires.

Table 1. Physical characteristics of study sites in the Pacific Northwest, USA. Geographic location by site code is depicted in Fig. 1. AC = active channel. Valley constraint was calculated by dividing average valley width by average active channel width (averages based on measurements taken every 20-m longitudinal interval within a site).

Stream	Site Code	Order	Stream gradient (%)	AC width (m) ¹	Valley constraint
<u>Interior Columbia Basin</u>					
N.F. Cabin Creek, OR	ICB1	2	7	4.1	25.7
S.F. Cabin Creek, OR	ICB2	2	7	4.4	15.1
Piper Creek, MT ²	ICB3	3	1	9.3	2.5
Bloom Creek, ID	ICB4	2	6	3.4	11.3
Murr Creek, MT	ICB5	2	6	5.4	2.9
Big Creek, WA	ICB6	4	3	13.0	2.0
Little Creek, WA	ICB7	3	4	7.0	2.1
Squeezer Creek, MT	ICB8	3	12	11.5	2.2
W.F. Mica Creek, ID	ICB9	2	5	2.5	9.6
Goat Creek, MT	ICB10	3	4	8.0	2.3
<u>West of Cascades crest</u>					
Sturdy Creek, OR	W1	3	11	11.8	2.3
Forks Creek, WA	W2	3	1	12.8	2.3
N.F. Gate Creek, OR	W3	3	12	11.4	1.9
Green Canyon Creek, WA	W4	3	10	8.7	3.4
Stillman Creek, WA	W5	3	2	4.4	3.5
Crim Creek, WA	W6	3	2	10.5	1.2
Hagan Creek, OR	W7	3	13	11.3	3.3
McCain Creek, WA	W8	3	10	10.6	6.9
Flynn Creek, OR	W9	3	8	11.9	2.4
Cedar Creek, OR	W10	4	8	11.6	1.3
Mack Creek, OR	W11	3	13	9.2	2.5
Overall:	--	--	7 (4)	8.7 (2.3)	5.1 (1.6)

¹Averages

²Western redcedar on one terrace were ~200 years old

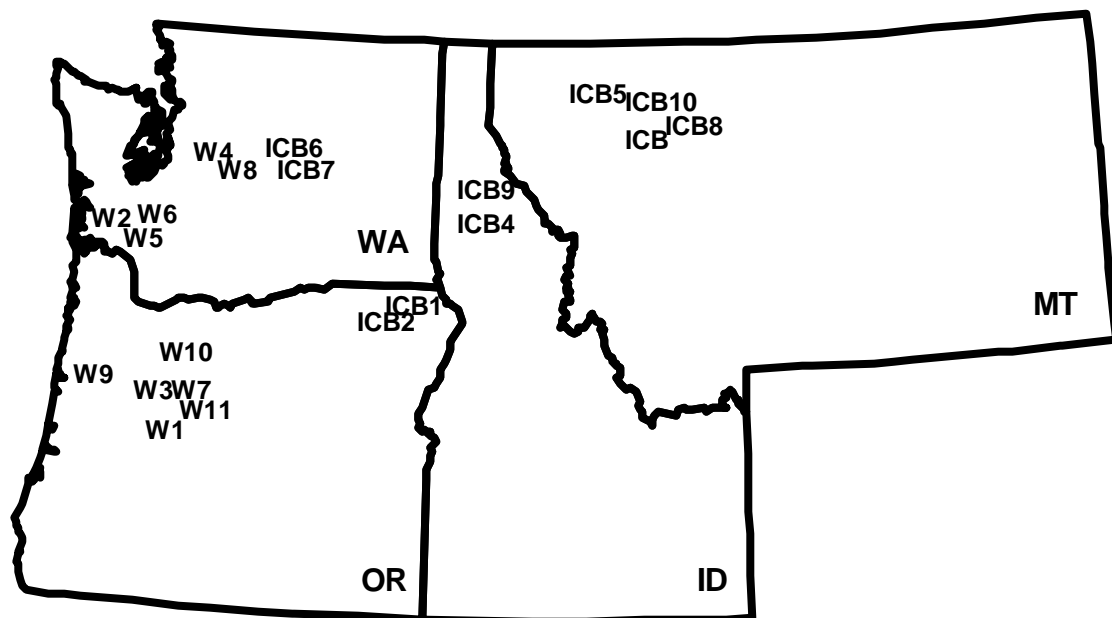


Fig. 1. Location of study sites in the Pacific Northwest, USA. W = west of the Cascades crest, ICB = Interior Columbia Basin (note: WA is the state of Washington). Letter/number combinations are site codes in Table 1.

METHODS

Rather than conducting transect sampling of down trees at each site, we instead performed exhaustive inventories to include = 30 down trees per site to satisfy requirements for statistical analyses of circular data without using bootstrap techniques (Fisher 1993). At S.F. Cabin and N.F. Cabin Creeks, OR, 10 and 16 trees were found, respectively. Because they did not meet our sampling number criteria, we removed them from site-level analyses.

The minimum size criteria for a measurable down tree were a diameter at breast height (dbh) = 10 cm and a height = 5 m. Azimuth of fall direction relative to the stream valley axis was recorded for each down tree (standardization: 0° = upstream; 90° = towards stream for both banks). We also recorded species, tree size (dbh and tree height), fall type (root throw versus stem break), rooting position (geomorphic landform where tree once stood), side slope to the channel at the base of the tree (%; $m \cdot m^{-1}$) and ground distance of the tree base to margin of active channel. Species was determined from bark morphology, branch structure and leaf or needle characteristics if present (Harlow and Harrar 1968). Tree dbh was measured by standard methods using dbh-corrected tapes (Avery and Burkhart 1994). Tree height was measured in the field to provide conservative estimates of height at time of fall. We did not estimate tree height from pre-established taper equations. Trees spanning streams with missing pieces in the channel were measured from the base to the end of the piece on the far side assuming the gap missing in the channel was the missing length. As an additional index of tree geometry, we calculated ratio of tree height/dbh (m/m). Tree height/dbh ratios approaching 100 indicate that internal stand thinning is taking place or has occurred (Oliver and Larson 1990). Originally, rooting position was classified as active channels, floodplains, terraces and hillslopes (Gregory 1997). Because < 30 trees were recorded for each of active channels and floodplains among all sites, we consolidated these trees into a group referred to as “valley bottoms.”

In addition to individual tree characteristics, forest structure along each site was measured. Stand density (trees·ha⁻¹), basal area (m²·ha⁻¹) and hardwood composition (percent of basal area) of the forest (dbh > 0.1 m) 50 m upslope of the active channel were measured with the point-center quarter method (Cottam and Curtis 1956). At least one (preferably two, depending on time constraints) transect(s) consisting of five equidistant plot centers beginning 5 m perpendicular upslope from the active channel were determined from compass bearings on each streamside at randomly selected 20-m longitudinal intervals within the site. We also calculated ratio of tree height/dbh of down trees to characterize tree geometry specific to individual sites. Height/dbh ratios approaching or > 100 indicate competitive exclusion (Oliver and Larson 1990). Before analyses with fall direction data, we assessed trends in basal area, density, % hardwood basal area and height/dbh ratio values over the gradient of forest age and between regions (indicator variable) with multiple linear regression techniques (Snedecor and Cochran 1989). Forest structure variables were designed to provide general information on riparian forest source of wood entering streams. Measurement of forest structure gradients according to microtopographic variation within sites was not possible with this sampling design.

For all analyses, α was set to the 5% level. Site-level fall distributions were tested for randomness against an unspecified unimodal alternative with Rayleigh tests (Fisher 1993) to determine frequency of sites with directional versus random fall. We calculated average fall direction and circular standard

deviation (hereafter referred to as CSD) with vector addition (Fisher 1993; Appendix A). We pooled down trees among sites and then divided them by categorical descriptions (species type and rooting position) and ranked groups condensed from continuous distributions of tree size (dbh, tree height and height/dbh) and side slope to the channel. We additionally calculated summary statistics of fall directions at each individual site. For all sets of analyses, average fall directions fell within 180° of each other, indicating that distances between values were not distorted (example of distortion: 5° and 355° are 10° apart, not 350° as determined from linear statistics). CSD alone is a weighted measure and thus does not have the potential for distortion among values.

Differences of fall directions based on species type were tested with an analysis of variance *F*-test (ANOVA) with individual trees pooled among sites as the response variable. Difference based on rooting position (valley bottoms versus hillslope) was tested with a two-tailed *t*-test. Following the species-level ANOVA, fall directions were compared with the Bonferroni-corrected 95% confidence intervals (CI) (Snedecor and Cochran 1989). We also analyzed percent of root-thrown versus stem-broken trees in both species- and rooting position-levels of analyses with χ^2 -tests to assess differences in fall types among groups (Snedecor and Cochran 1989).

Down trees pooled from all sites were ranked by groups for regression analyses of fall directions as a function of tree size, tree geometry and side slope of rooting position. We chose to use ranked groups instead of individual

trees because these groups commonly are used in forestry practices (e.g., Oregon Department of Forestry 1994) and this technique allowed analysis of average fall direction and CSD among ranked groups. For tree size analyses, we divided trees into separate dbh and tree height groups. For dbh groups, trees were divided into 10-cm intervals beginning with the 10-20 cm class and ending with a > 1 m class. For tree height, trees were divided into 5-m intervals beginning with the 5-10 m class and ending with a > 35 m height class. Groups based on tree geometry were divided into 10-m/m intervals of tree height/dbh classes starting with the 0-10 m/m class and ending with a > 100 m/m class. Lastly, we divided trees by 10% interval side slope classes beginning with slopes 0-10% and ending with slopes > 90%. Within each ranked group, we calculated average fall direction and CSD for each ranked group and then used simple regression analyses and *t*-tools to assess trends in average fall direction and CSD.

Associations of site-level average fall direction and CSD with stream valley geomorphology, forest structure, forest age class and region were evaluated with a series of regression models and two-way ANOVAs. We constructed models of average fall direction and CSD as functions of stream valley constraint, average active channel width, forest density, forest basal area, percent of basal area in hardwoods and tree height/dbh ratio. We did not distinguish forest age class (40-60, 80-150 and > 150 years old) or regional location (WCC versus ICB). Instead, associations of average fall directions and CSDs with regional location blocked by forest age class were

tested with two sets of two-way ANOVAs (fixed effects without interaction terms) (Snedecor and Cochran 1989).

For regression analyses, linear models were used unless inspection of graphical depictions indicated that nonlinear models were more appropriate. Analyses were conducted with S-Plus 2000 (MathSoft, Inc.; Seattle, WA).

RESULTS

FIELD RESULTS

Ten to 100 down trees were measured at each study site. Overall, 1202 down trees were measured (Table 2). We included all down trees in site-level analyses. For analyses that pooled trees among sites, 117 down trees were removed (adjusted $N = 1095$). These trees were taken out because either they were one of eight species that represented $< 1\%$ of the total number tree surveyed or the species was not identified. A total of eight species were included in the pooled analysis of tree species: Douglas-fir, western redcedar, red alder (*Alnus rubra* Bong.), Engleman spruce (*Picea englemanii* Parry), western hemlock, lodgepole pine, western larch and grand fir (Table 3). We also divided Douglas-fir by Coast and Interior forms because

these variants have different life histories and structural morphologies (Harlow and Harrar 1968).

Forest structure was highly variable among sites (Table 2). Basal area did not show a linear trend with increasing forest age after removing effects of region ($p=0.21$; $r^2=0.06$; $F=1.7$; 2, 16 d.f.). Also, forest density did not show a linear trend with increasing forest age after removing effects of region ($p=0.19$; $r^2=0.07$; $F=1.8$; 2, 16 d.f.). Ratio of tree height/dbh slightly decreased with stand age regardless of regional location ($p=0.06$; $F=4.8$; 1, 17 d.f.). This trend is consistent with stand development theories (Oliver 1981; Oliver and Larson 1990). Percent of hardwood basal area ranged from 8 to 24% except for one site (Crim Creek, WA had 44%) and did not vary with forest age or between regions ($p=0.42$; $F=0.9$; 2, 16 d.f.). Hardwoods typically are understory and early-successional species in northwest riparian forests (Oliver and Larson 1990; Swanson et al. 1998), though recent studies suggest that hardwoods locally persist as overstory trees for centuries both in floodplains and uplands in the Coast Range of Oregon and Washington (Nierenberg and Hibbs 2000).

Of the 19 sites that met sampling criteria ($n = 30$ down trees), 17 had unimodal fall directions ($p<0.05$) while two did not pass the Rayleigh test for directional unimodal fall (Table 3). Of sites with significant unimodal fall directionality, 14 were generally towards stream channels while three were oriented up the stream valley axis (Table 3).

In pooling trees among sites, average fall directions differed among species ($p < 0.0001$; $F = 6.7$; 8, 1086 d.f.). The most notable differences occurred with western larch and lodgepole pine (Table 4). These two species fell most upstream (average \pm CSD of $37 \pm 42^\circ$ and $59 \pm 52^\circ$, respectively) and differed from the other seven species ($p < 0.0001$; Bonferroni-corrected intervals). All other species predominantly fell towards channels ($73^\circ < \text{average fall} < 89^\circ$). CSD ranged from ± 42 to $\pm 83^\circ$ by species. Douglas-fir (both Coast and Interior forms) and grand fir fell most directly towards stream channels ($85^\circ < \text{average fall} < 89^\circ$) with the least amount of variation (± 44 to $\pm 45^\circ$ SD) (Table 4). Red alder and Engleman spruce had the largest fall variance (CSD of ± 61 and $\pm 83^\circ$, respectively). These two species also had the highest percent of trees originally located on valley bottoms (58-59%); all other species had $< 38\%$ of individual trees on these landforms (lowest was 12% for grand fir). Root-thrown trees ranged from 63 to 83% for each species (Douglas-fir Interior and Douglas-fir Coast, respectively) and differed among species ($p = 0.03$; $\chi^2 = 17.0$; 8 d.f.) (Table 4).

Table 2. Riparian forest structure along study sites in the Pacific Northwest, USA.

Stream	Forest age (years)	Forest density (trees·ha ⁻¹)	Basal Area (m ² ·ha ⁻¹)	Tree height/dbh (m/m)
<u>Interior Columbia Basin</u>				
N.F. Cabin Creek, OR	40	624	89	64
S.F. Cabin Creek, OR	40	450	48	63
Piper Creek, MT ¹	50	960	97	55
Bloom Creek, ID	50	623	47	69
Murr Creek, MT	90	1751	61	83
Big Creek, WA	150	444	68	87
Little Creek, WA	150	292	125	48
Squeezer Creek, MT	200	1313	134	52
W.F. Mica Creek, ID	>200	431	102	38
Goat Creek, MT	200	1162	116	58
<u>West of Cascades crest</u>				
Sturdy Creek, OR	40	1022	72	67
Forks Creek, WA	40	771	53	61
N.F. Gate Creek, OR	50	346	20	65
Green Canyon Creek, WA	60	919	41	86
Stillman Creek, WA	60	498	155	73
Crim Creek, WA	80	193	78	40
Hagan Creek, OR	110	202	75	45
McCain Creek, WA	120	447	42	63
Flynn Creek, OR	170	185	35	38
Cedar Creek, OR	500	570	38	53
Mack Creek, OR	500	199	54	41

¹Western redcedar on one terrace were ~200 years old

Table 3. Summary of number of down trees (n), reach length and fall directions by site, Pacific Northwest, USA. Circular standard deviations are in parentheses following average fall direction. For average fall, 0° = upstream; 90° = towards stream. Rayleigh test is a probability test for a random distribution versus an unspecified unimodal alternative (Fisher 1993).

Stream	n	Reach (m)	Average fall (degrees)	Rayleigh test (p)
<u>Interior Columbia Basin</u>				
N.F. Cabin Creek, OR ¹	10	300	91 (9)	Bootstrap
S.F. Cabin Creek, OR ¹	16	300	18 (28)	Bootstrap
Piper Creek, MT	99	220	121 (74)	0.11
Bloom Creek, ID	50	300	16 (45)	<0.0001
Murr Creek, MT	100	260	7 (59)	<0.0001
Big Creek, WA	60	300	94 (42)	<0.0001
Little Creek, WA	47	300	99 (57)	<0.0001
Squeezer Creek, MT	100	200	128 (64)	0.003
W.F. Mica Creek, ID	50	300	88 (57)	<0.0001
Goat Creek, MT	100	200	110 (39)	<0.0001
<u>West of Cascades crest</u>				
Sturdy Creek, OR	31	300	85 (50)	0.004
Forks Creek, WA	50	300	8 (60)	<0.0001
N.F. Gate Creek, OR	51	300	117 (61)	0.02
Green Canyon Creek, WA	50	200	61 (53)	<0.0001
Stillman Creek, WA	50	240	91 (44)	<0.0001
Crim Creek, WA	43	300	118 (53)	<0.0001
Hagan Creek, OR	30	300	91 (80)	0.71
McCain Creek, WA	50	200	75 (66)	0.008
Flynn Creek, OR	66	300	96 (49)	<0.0001
Cedar Creek, OR	51	300	90 (68)	0.02
Mack Creek, OR	98	200	104 (36)	<0.0001
Overall:	1202	5620	90 (26)	<0.0001

¹not used in site-level regression models or ANOVA.

Table 4. Summary of down trees across study sites. These species represent > 99% of the total number of down trees measured. Coefficients of variation (%) are in parentheses for geometric means of diameter at breast height (dbh) and height; circular standard deviations are in parentheses following average fall directions. Valley bottoms include terraces, floodplains, and active channels. For average fall, 0° = upstream and 90° = towards stream. Differing superscript letters in species and rooting position categories refer to statistically significant differences of fall directions ($p < 0.0001$ in all cases; Bonferroni method for species and t -based intervals for rooting position).

Species	<i>n</i>	Geometric mean		Root thrown (%)	Average fall (degrees)	
		dbh	height			
Douglas-fir (Coast)	255	0.37 (127)	17 (89)	83	89 ^a	(45)
Western redcedar	184	0.36 (102)	14 (85)	80	77 ^{ab}	(56)
Red alder	178	0.25 (80)	12 (60)	68	78 ^{ab}	(61)
Engleman spruce	121	0.26 (61)	15 (69)	68	75 ^{abc}	(83)
Douglas-fir (Interior)	105	0.23 (75)	12 (63)	63	87 ^{ab}	(47)
Western hemlock	100	0.20 (62)	13 (66)	71	73 ^{abc}	(54)
Lodgepole pine	64	0.19 (75)	15 (59)	64	59 ^{bc}	(52)
Western larch	56	0.45 (53)	21 (54)	66	37 ^c	(42)
Grand fir	32	0.16 (32)	12 (52)	81	86 ^{ab}	(44)
Rooting position						
Valley bottoms	391	0.29 (103)	15 (80)	70	77 ^a	(72)
Hillslope	704	0.28 (96)	14 (74)	72	88 ^b	(48)
All down trees	1095	0.28 (99)	14 (76)	70	89	(55)

Average fall direction differed between valley bottom and hillslope trees ($p < 0.0001$; $t = 3.2$; 1093 d.f.) (Table 3). Though average fall directions of down trees from both landforms were oriented towards channels (hillslope = 88° and valley bottoms = 77°), CSD of valley bottom trees was almost twice that of hillslope trees ($\pm 72^\circ$ versus $\pm 48^\circ$). On an ancillary note, we found that fall type was not auto-correlated with rooting position. Percent of trees that were stem

broken versus those that were root thrown did not significantly differ between rooting positions ($p=0.46$; $c^2=0.5$; 1 d.f.).

In general, tree fall was oriented towards channels regardless of tree size, tree geometry or side slope steepness (Fig. 2 and 3). Average fall directions typically centered on 90° among ranked groups except for several individual classes (Fig. 2 and 3). Tree height was the only parameter significantly associated with average fall direction ($p=0.03$; $r^2=0.66$; $F=9.6$; 1, 5 d.f.) (Fig. 2D). Average fall direction was observed to change from 83° in the 5-10 m height class to 68° in > 35 m class. In groups of tree geometry and slope steepness, two individual classes had average fall directions that were closer to the upstream axis than towards the channel (Fig. 2G and 3). In the tree geometry group, the 90-100 m/m class had an average fall direction of 357° . This group also had one of the lowest numbers of trees (37 trees whereas all other groups, except one, had > 73 trees) and highest variance (CSD of $\pm 55^\circ$) (Fig. 2G, 2E and 2F). As for the side slope group, only the 20-30% slope class had a fall direction closer to upstream than towards the channel ($39 \pm 56^\circ$) (Fig. 3A). Overall, average fall direction did not change with steeper side slope classes and was consistently towards the channel ($p=0.18$; $r^2=0.21$; $F=2.2$; 1, 8 d.f.).

Variance of riparian tree fall directions exhibited a shift from gentle to steep slopes (Fig. 3 and 4). Though average fall direction remained similar across slope classes (except for the 20-30% class), CSD decreased from slopes 0-10% to $> 90\%$. CSD of fall directions was significantly larger on side

slopes < 40% compared to that on steeper side slopes by 22 to 44° (95%

CI) (Fig. 4). CSD of ranked groups of down trees on slopes < 40% was $73 \pm$

11° (average \pm standard deviation (SD)) while on slopes > 40% the CSD was 40

$\pm 3^\circ$.

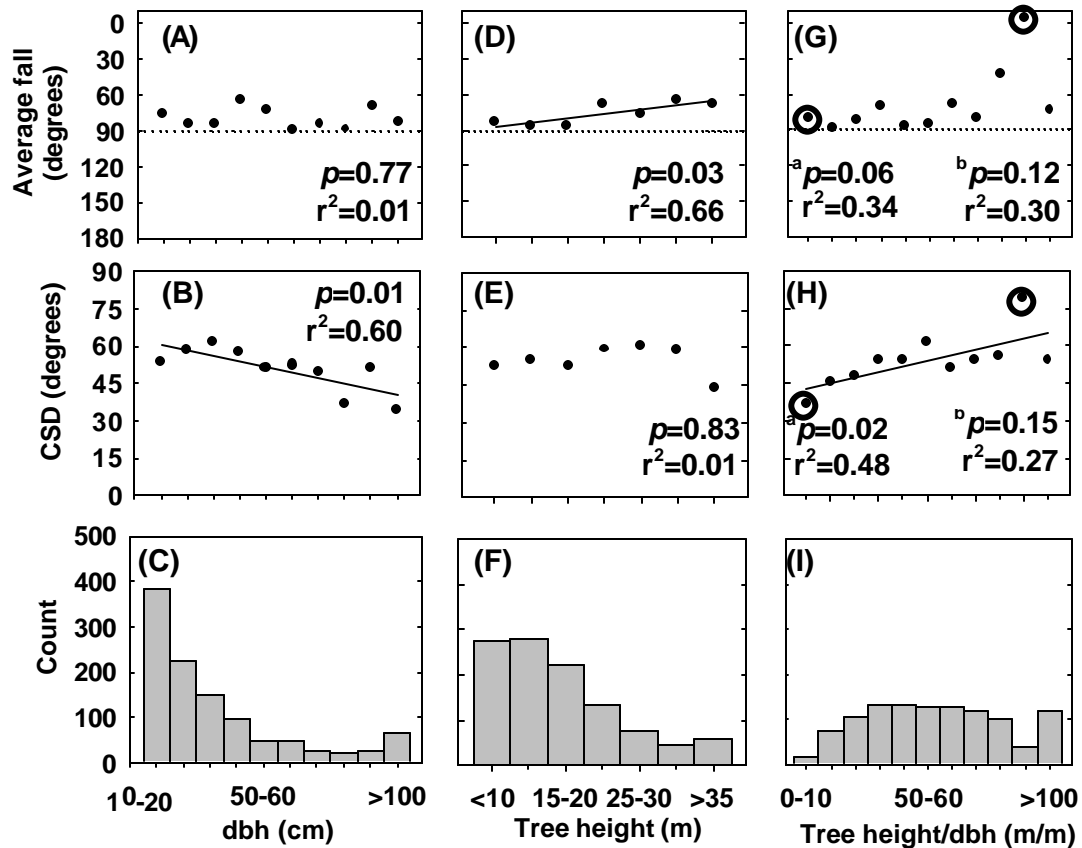


Fig. 2. Riparian tree fall directions as a function of tree size characteristics across study sites in the Pacific Northwest, USA. Ranked groups of tree size and tree geometry versus (graphs A, D, and G) average fall direction, (graphs B, E, and H) circular standard deviation (CSD), and (graphs C, F, and I) count frequency of ranked groups. The equation in (B) is $y = 63 - 2.2 * x$ and the one in (D) is $y = 90 - 3.5 * x$. In graphs (G) and (H), circled points refer to the 0-10 and 90-100 height/dbh classes (they had the lowest number of replicates among all ranked groups: 15 for the 0-10 class and 34 for the 90-100). The (a) superscript in these two graphs refers to models including the two classes; (b) refers to their removal. In graph (H), the equation for (a) is $y = 41 + 2.2 * x$. In graphs (A), (D), and (G), dotted lines are towards channel; zero is up the stream valley. In all cases, x is an integer rank based on the number of group classes (e.g., dbh has 10 classes; x takes a value 1-10 in the equation).

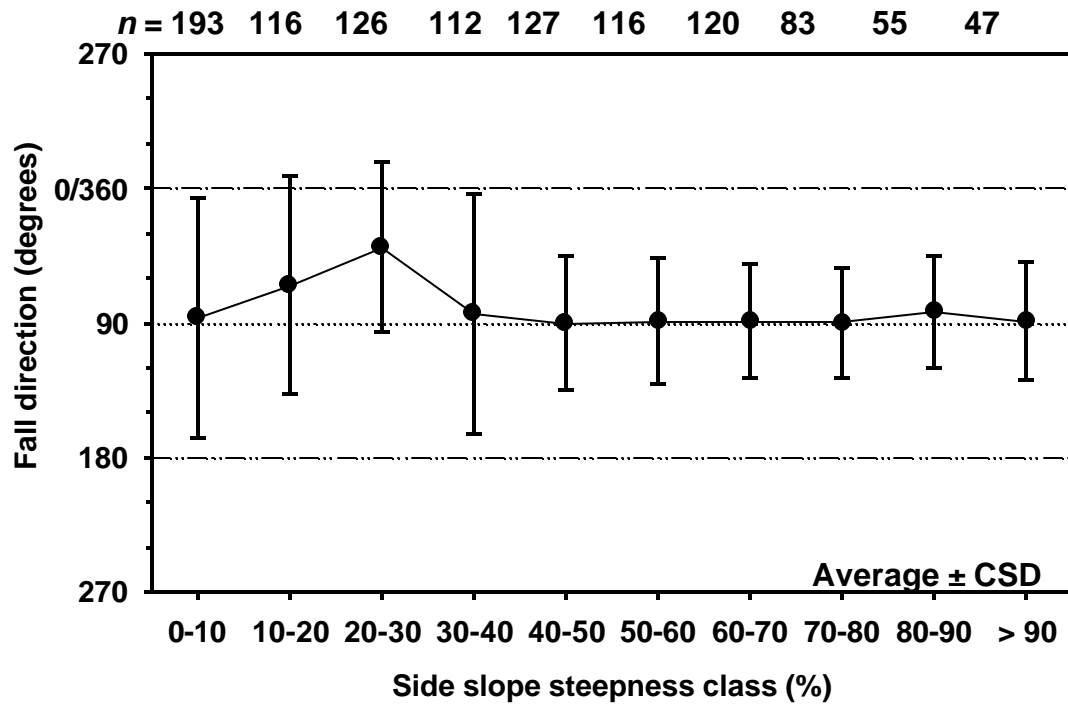


Fig. 3. Plots of riparian tree fall directions as a function of side slope steepness classes across study sites in the Pacific Northwest, USA. Numbers of trees comprising each class are listed at the top of the figure. Fall direction scale is: away from stream = 270° ; upstream = $0/360^{\circ}$; toward stream = 90° ; downstream = 180° . CSD is circular standard deviation.

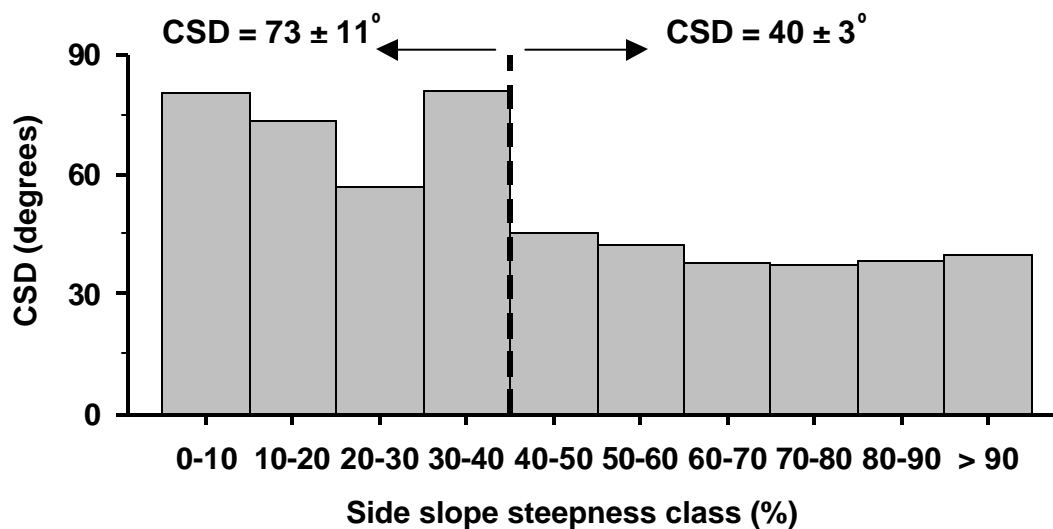


Fig. 4. Circular standard deviation (CSD) of tree fall directions as a function of side slope steepness classes across study sites in the Pacific Northwest, USA. Values are averages \pm standard deviations. See Fig. 3 for sample sizes in each ranked class.

Tree dbh also was associated with CSD ($p=0.001$; $r^2=0.59$; $F=11.7$; 1, 8 d.f.), but ecological significance of this relationship was questionable. CSD decreased only by 2° for every 10-cm interval increase in dbh class (95% CI of 1 to 3°) (Fig. 2B). Moreover, distribution of dbh was strongly right-tailed skewed whereas trees were evenly distributed across slope steepness classes (Fig. 2C and 3). Thus, the pattern of CSD as a function of dbh may result from the strong right-tailed skew in class sample sizes. Geometric mean of dbh ranged from 0.25 to 0.37 m among slope classes with a slight (3%) increase in dbh for every 10% slope interval increase. Also, geometric mean tree height slightly increased from 14 to 16 m from gentle to steep side slopes.

Two classes that had the lowest numbers of replicates among ranked groups drove fall direction models with tree height/dbh as the explanatory variable. The 0-10 m/m class was comprised of 15 trees and the 90-100 m/m class had 34 trees. All other classes had > 73 trees. Initially, average fall direction and CSD were associated with tree height/dbh ($p=0.06$ and 0.02 , respectively; $r^2=0.34$ and 0.48 ; $F=4.6$ and 8.4 ; 1, 8 d.f. each) (Fig. 2H and 2I). Removal of the 0-10 and 90-100 m/m classes from both models resulted in lower statistical significance ($p=0.12$ and 0.5 respectively; $F=3.0$ and 2.6 ; 1, 6 d.f.) and variance explained ($r^2=0.30$ and 0.28 , respectively).

Regression models of fall direction as functions of valley constraint and active channel width were not significant ($0.10 < p < 0.75$; $0.1 < F < 2.9$; 1, 17 d.f. each). These models explained less than 10% of the variance in either average fall direction or CSD. Similar results were observed for measures of forest structure. Average density and basal area, as well as percent of basal comprised of hardwoods, were not associated with average fall direction or CSD ($0.10 < p < 0.65$; $r^2 < 0.13$ in all cases; $0.2 < F < 3.1$; 1, 17 d.f. each). Average fall direction was mildly associated with average tree height/dbh ratio ($p=0.06$; $r^2=0.19$; $F=3.9$; 1, 17 d.f.) (Fig. 5A). In this model, sites with upstream fall had tree height/dbh ratios > 50 m/m. An additional site with average fall intermediate to upstream and towards the channel (61°) had a tree height/dbh ratio of 83 m/m. This suggests that variation in average fall direction was greater at sites with relatively thin trees compared to sites with

thick trees. CSD was not associated with site-averaged tree height/dbh

($p=0.40$; $r^2=0.04$; $F=0.8$; 1, 17 d.f.) (Fig. 5B).

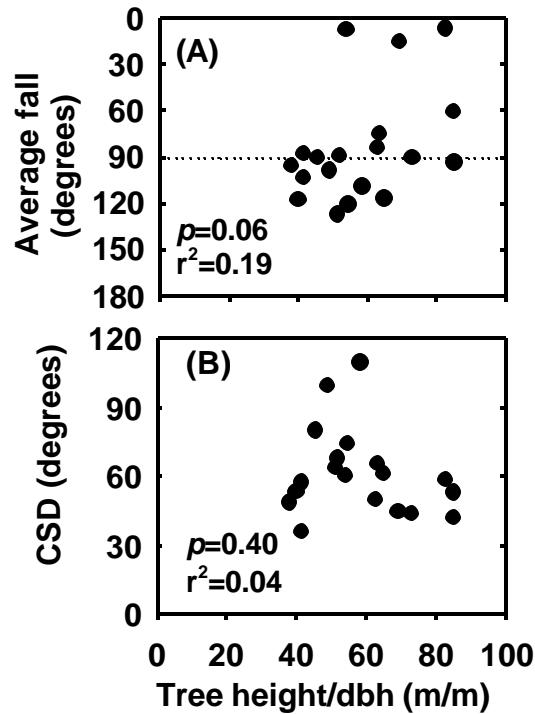


Fig. 5. Riparian tree fall directions as a function of site-averaged tree height/dbh ratios in the Pacific Northwest, USA. (A) Average fall direction and (B) circular standard deviation (CSD). Models do not distinguish regional locations. In graph (A), dotted line refers to towards channel; zero is up the stream valley.

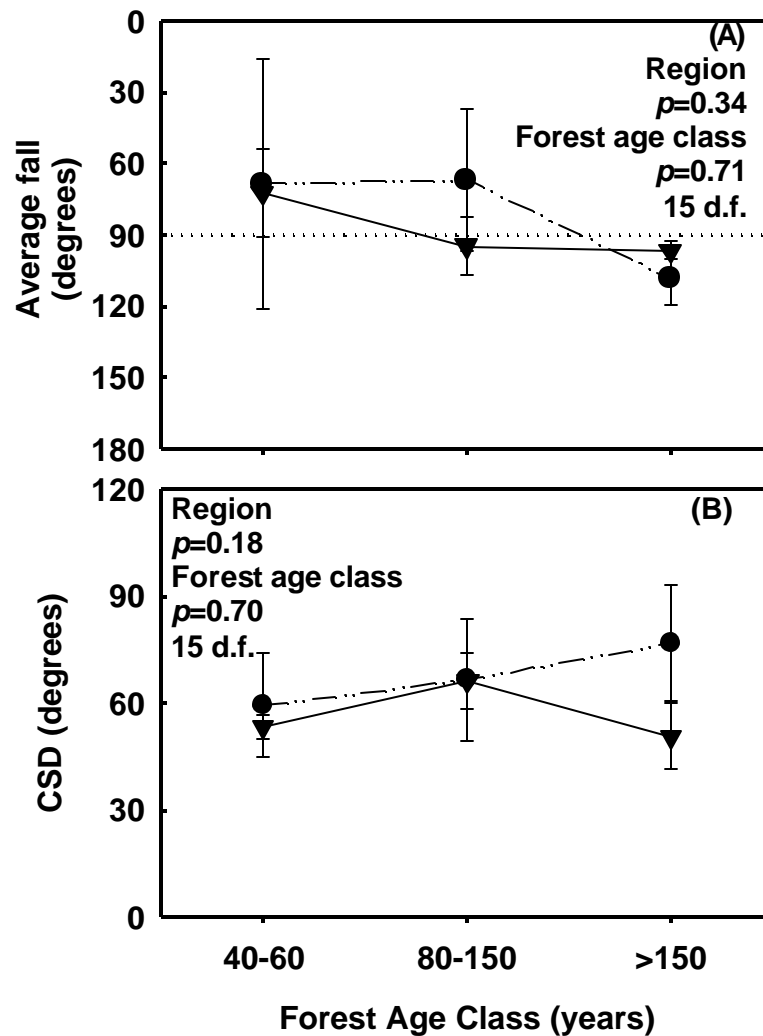


Fig. 6. Riparian tree fall directions as a function of forest age class grouped by regional location in the Pacific Northwest, USA. (A) Average fall direction; Dotted line refers to towards channel; zero is up the stream valley. (B) Circular standard deviation (CSD) (bars represent one standard error in each graph). (●) Interior Columbia Basin and (▼) west of Cascades crest.

Site-level fall directions did not differ among forest age classes or by region (Fig. 6). Average fall directions did not differ among forest age classes after removing effects of regional location ($p=0.34$) or regional location after removing effects of forest age class ($p=0.71$) ($F=1.2$ and 1.1 , respectively; 2,

15 d.f.) (Fig. 6A). Additionally, CSD was not associated with forest age class after removing effects of regional location ($p=0.70$) or with regional location after removing effects of forest age class ($p=0.18$) ($F=0.6$ and 1.4 , respectively; 2, 15 d.f.) (Fig. 6B).

TREE FALL MODEL

The probability of a tree falling directly into a stream channel is a function of tree height (h), distance to the channel (z), and a probability density function $f(a)$ for fall angle a , expressed in degrees (Van Sickle and Gregory 1990).

$$[1] \quad P_s = \int_{a_s}^{180-a_s} f(a) da$$

P_s is probability of entering the channel and $(a_s, 180-a_s)$ is the circular arc within which falling trees can hit the channel [$a_s = \sin^{-1}(z/h)$] (Van Sickle and Gregory 1990). For random fall directions, $f(a)$ is a uniform distribution (McDade et al. 1990), and

$$[2] \quad P_s = (\cos^{-1} z/h)/180.$$

To explore potential influences of side slope to the channel on wood delivery to streams, we used an approximated normal probability density function ($f(a)$ in eq. 1) based on our field data on fall directions. Because we are using circular means and standard deviations, we cannot exactly rescale angles to a standard normal curve (Fisher 1993). But, because observed circular standard deviations are relatively small (Fisher 1993), we can approximate P_s based on

$$[3] \quad P_s = P\left(\frac{a_s - \mu}{s} < U < \frac{(180 - a_s) - \mu}{s}\right)$$

where μ and σ are the mean and standard deviation of fall direction and U is a random variable from the Standard Normal Distribution (Snedecor and Cochran 1989).

Additionally, expected mean number of falling trees intersecting the channel (N) per unit stream length over a specified time period within the bounds of 0 to h distance upslope can be calculated according to

$$[4] \quad E(N) = DLP_F \int_0^h P_s(z) dz$$

where D is the riparian stand density, L is stream reach length, and P_F is the probability of tree fall (Van Sickle and Gregory 1990). By calculating P_s

according to eq. 3 and holding D , L , P_F , and h constant, we can calculate relative differences in total inputs between two different fall patterns by dividing the area under one P_s curve by the area of the other curve over h (Van Sickle and Gregory 1990).

Additionally, we can calculate cumulative number of trees falling into a stream from any given distance upslope from the stream (McDade et al. 1990). To do so, we calculated $P_s(z)$ for a given height class h at 1-m intervals from 0 to h distance away from the stream. Next, the proportion of the total number of trees entering from each 1-m interval is calculated by dividing $P_s(z)$ for each 1-m interval by the sum of all $P_s(z)$ from 0 to h . Cumulative percent of trees entering from any given distance z is calculated by summing the proportion of the total number of trees entering the stream for each 1-m interval from 0 to z distance (McDade et al. 1990).

To incorporate our field data, we calculated relative differences of (1) total number of trees falling into channels and (2) cumulative probability of channel entry by falling trees among random fall directions and directional fall on side slopes 0-10% and side slopes > 90%. We set tree height to 50 m for illustrative purposes; relative differences between fall patterns remains constant if height is kept constant for comparisons. We calculated random fall (eq. 2) and set $\mu = 90^\circ$ for calculating P_s on gentle (0-10%) and steep (> 90%) side slopes (from eq. 3) because results suggest an average of fall towards channels. We assigned the observed CSD values in the slope class of 0-10% and > 90% as σ (slopes 0-10% = 80° ; slopes > 90% = 40°). However, note

that average fall directions appeared more variable on slopes < 40% and may strongly effect probability of tree fall into the stream (Appendix B).

Comparisons of the areas under curves of P_s for random fall and direction fall on gentle and steep side slope classes reveal that fall directions on steep side slopes produced 2.5 and 1.5 times more falling trees entering the channel than random fall directions and fall directions from slopes 0-10%, respectively (Fig. 7A). In comparison, the difference between complete towards channel fall ($\mu = 90^\circ$; $\sigma = 0^\circ$) versus random fall is exactly π (3.14) (Van Sickle and Gregory 1990).

Common riparian buffer widths for small, fish-bearing streams on state and private lands in the Pacific Northwest range from 20 to 30 m (75 to 100 ft.) upslope from the channel (Gregory 1997). We can estimate percent of total wood (by numbers) recruited from any given distance upslope from the stream base on tree height and fall direction (McDade et al. 1990). At 30 m ground distance from the stream, random tree fall directions will provide 77% of the total number of 50-m tall trees that can potentially fall into stream while directional fall on slopes > 90% supplies 71% of the total number of trees that potentially can fall into the stream. In other words, directional tree fall towards the stream, as indicated for steep slopes, supplies a slightly greater number of trees to the stream from farther upslope of the channel compared to tree inputs under a random fall regime (increase by approximately 8% in the previous example) (Fig. 7B).

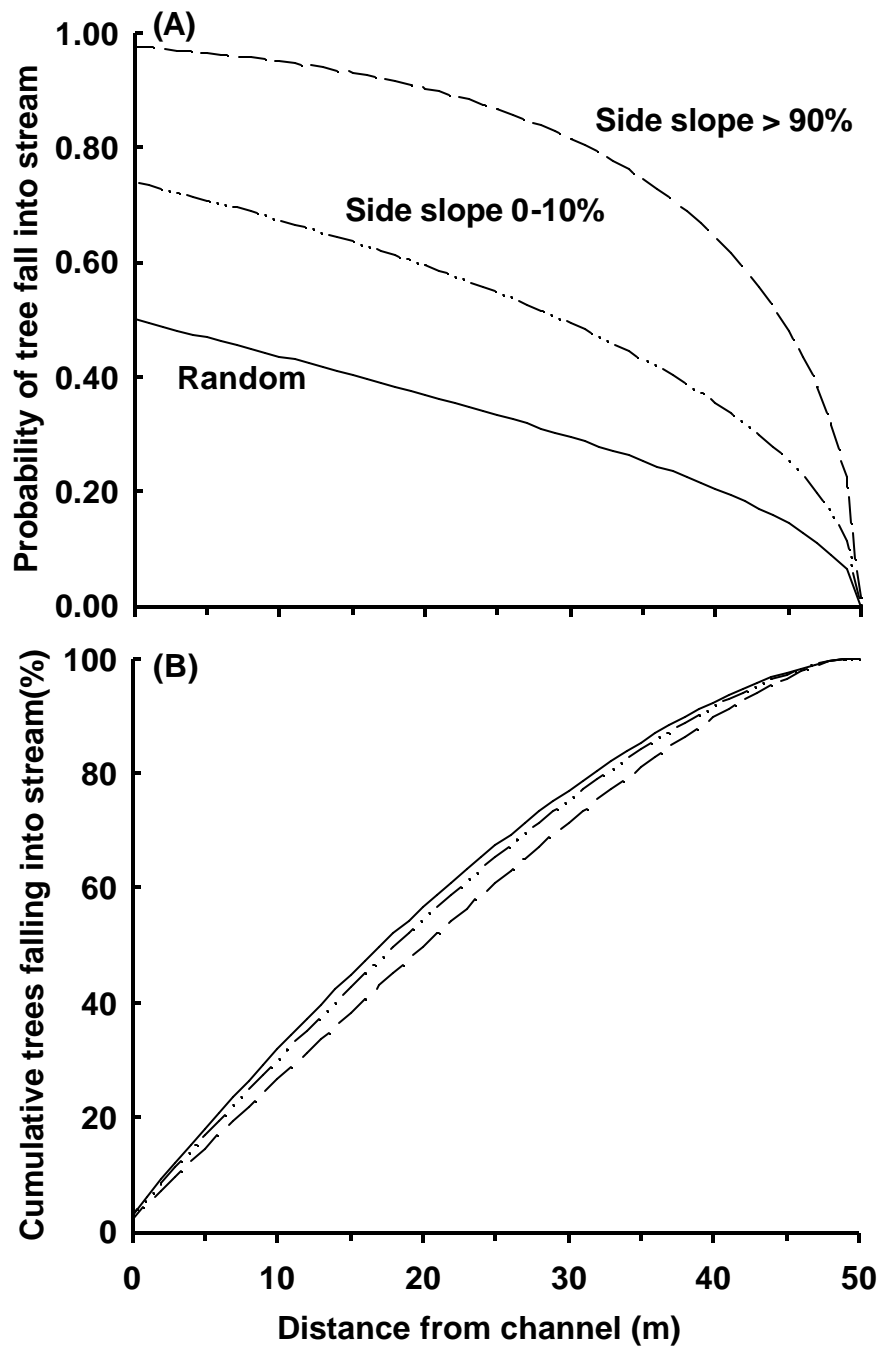


Fig. 7. (A) Probability of tree fall into a stream and (B) cumulative delivery of falling trees as a function of distance from the channel (50-m height class). Fall directions for each scenarios were as follows: random: 1/360 chance to fall in any direction; side slopes 0-10%: $\mu = 90^\circ$, $\sigma = 80^\circ$; side slopes > 90%: $\mu = 90^\circ$, $\sigma = 40^\circ$.

DISCUSSION

Accuracy and broad application of models of wood dynamics in stream ecosystems is partially limited by representation of wood recruitment rates and patterns (Meleason 2001). In most current models, recruitment of wood is controlled by dynamics of forest mortality, rate of fall and fall direction (Van Sickle and Gregory 1990; Beechie et al. 2000; Welty et al. 2001). Simulation models of stand dynamics have been indicated to reasonably estimate structural and compositional development of forests in the Pacific Northwest (e.g., JABOWA, Botkin 1993; ORGANON, Welty et al. 2001). The major problem has been accurate representation of the fall process (Van Sickle and Gregory 1990; Beechie et al. 2000; Meleason 2001). Rate of tree fall is difficult to determine without long-term field surveys because trees do not necessarily fall in the same year that they die (Bragg et al. 2000; Beechie et al. 2000). Though this research did not measure fall rates, we found several interesting trends in tree fall directions. On average, trees generally fell towards channels regardless of species, tree size, tree geometry, rooting position away from the channel or side slope steepness. However, representing fall directionality only by an average can be misleading because variance of fall directions changed significantly according to several environmental factors. By incorporating both mean and variance of riparian tree fall directions in probabilistic-based models (e.g., Van Sickle and Gregory

1990), more accurate projections of wood recruitment from riparian forests can be produced.

The overall central tendency for trees to fall towards channels regardless of tree size and geometry, species, rooting position and side slope may reflect growth and structural responses of trees to natural canopy openings over stream channels (McDade et al. 1990; Robison and Beschta 1990). Trees lean and develop more branch mass toward canopy openings over streams in a phototropic-induced growth process (Bustos-Letelier 1994). Additionally, landslides and soil creep tilt the tree base downhill (Oliver and Larson 1990; Fantucci 1999). Structural failures on boles or destructive events (wind, snow/ice loading or impact from another falling tree) that destabilizes a tree base may thus cause fall towards channels regardless of tree species, tree size or side slope.

The decline in variance of tree fall directions from gentle to steep slopes may result from species- or individual-based differences in root and bole structure according to rooting position on valley bottoms versus hillslopes (Huber 1918; Alexander and Buell 1955; Gratkowski 1956; Lienkaemper and Swanson 1987). Trees rooting on hillslopes (well-drained soils) tend to have well-developed, deep rooting structures and strongly-braced boles while those growing next to streams (unconsolidated, poorly-drained soils with high water tables) tend to have shallow, wide-spreading root systems (Harlow and Harrar 1968; Lienkaemper and Swanson 1987). Douglas-fir, lodgepole pine and other species common on uplands tend to have well-developed and deep

rooting structures. Red alder, Engleman spruce and other species rooting next to streams have shallow, spreading root systems (Harlow and Harrar 1968). There are exceptions to these general patterns; for example, western hemlock was commonly found on uplands but has shallow roots (Harlow and Harrar 1968). Local conditions also may result in physiological and structural changes in individual trees. Soil creep, landslides and wind exposure cause formation of compression and tension wood in tree boles and continual structural readjustment to stress and force vectors to brace against falling over on hillslopes (Oliver and Larson 1990; Fantucci 1999). These patterns of structural development may directly affect variance of fall directions. Unstable rooting conditions next to streams may result in exposure to a wider range of atmospheric or high flow events capable of toppling trees and thus cause greater variance of fall directions compared to hillslopes, which may have less variance because of a narrower range of events capable of causing tree fall (Alexander and Buell 1955; Gratkowski 1956).

Wind is an important causal mechanism of tree fall events in riparian forests (Harmon et al. 1986; Lienkaemper and Swanson 1987; Robison and Beschta 1990). Orientations of down trees are frequently used to describe prevailing wind directions (Alexander and Buell 1955; Veblen 1986; Ott 1997). This research did not analyze tree fall in relation to winds for several reasons. Stands experience highest rates of damage from windstorms coming from unusual directions (e.g., from the northwest when storms usually come from the southwest) and where new clearings or canopy openings have recently

exposed trees to previously un-encountered winds (Grawtkoski 1956; Steinblums et al. 1984, Andrus and Froelich 1992; Esseen 1994). In addition, complex topography creates unpredictable wind directions (Lee 2000). Winds accelerate and change direction when funneled between mountains, over passes and along harvest boundaries (Gratkowski 1956; Ruel et al. 2001). Studies that use tree fall directions to quantify wind directions typically are located at high elevations (e.g., Alexander and Buell 1955; Veblen 1986) or on landscapes with relatively gentle relief (e.g., Ott 1997). Both of these topographic conditions provide the least opportunity for turbulent winds. Tree fall directions at individual sites were distributed similarly on both stream banks, indicating that the majority of tree fall was not caused by prevailing winds. We did not find differences in fall directions between fall types (root-thrown versus stem-broken), but this measure may be a poor characterization of the causal mechanism of tree fall (wind is traditionally thought to cause the majority of root throw). Because of the complexity and uncertainty of wind directions and force in highly-variable topographic settings, process-based models are unlikely ever to be capable of modeling wind effects on wood recruitment in a realistic way.

Riparian forest structure and composition fundamentally control availability of wood to streams (Liquori 2000). Most aspects of stand structure did not influence tree fall directions at our sites. Therefore, fall directions typically reflected a central tendency to fall towards channels regardless of environmental conditions. However, three sites with high tree height/dbh

ratios in down trees had general upstream fall directions. These sites are the only locations that may reflect low resistance to wind damage from storms funneling up the stream valley (Ruel et al. 2001). This suggests that an interaction among stand structure and causal mechanisms of tree fall counteract effects of valley geomorphology and topography. But, only three sites displayed this pattern; more extensive surveys are needed to confirm this behavior.

Regional location was not significantly associated with tree fall directions. This was surprising because of differences in overall forest composition between WCC and ICB sites. Mortality agents differ between these two regions, with snag development following standing death approximately 30% more common in the Interior region (Harmon et al. 1986). Also, fall directions did not differ by valley constraint or active channel width. Though these physical dimensions may not influence fall directions, valley constraint and channel width are critical factors in determining the functional status of wood in streams (Bilby and Ward 1989; Rot et al. 2000; Martin 2001).

This study focused on wood recruitment based on endogenous mortality (Bormann and Likens 1979) in riparian forests. Anomalous windstorms, debris flows, catastrophic floods, fires or other infrequent, spatially discrete catastrophic events (return interval of 10-100s of years) can locally be important for supplying wood to small streams in the Pacific Northwest (Benda and Sias 1998; Bragg 2000). Fire events can temporarily (~50 years) double wood volume in small streams (Benda and Sias 1998).

Debris flows following fire can further double stream wood volume for short time periods (~50 years) (Benda and Sias 1998). However, stream wood derived from these events may only comprise 10-15% of the standing wood volume at any one point in time when averaged across the landscape (Benda and Sias 1998). Transport from upstream is another source of wood to stream reaches (Lienkaemper and Swanson 1987; Murphy and Koski 1989; Martin and Benda 2001). Between 13 and 98% of the wood volume within 1-km sections of a small stream on the Oregon Coast was transported from an upstream source (McGarry 1994). In streams similar to ones in this study, tree fall caused by structural failure following mortality, competitive exclusion or atmospheric events are the chronic wood delivery mechanisms external to channel processes (Lienkaemper and Swanson 1987; McDade et al. 1990; Bragg et al. 2000).

Greater probability of fall towards channels on steep side slopes indicates an important consideration for assessing potential of riparian forests to deliver wood to adjacent streams. Approximately 2.5 times more wood (by numbers) is expected from slopes > 90% compared to random fall directions and 1.5 times more than from side slopes 0-10%, assuming similar riparian forest densities, basal areas and species compositions (Fig. 7A). Several states in the Pacific Northwest require 75-100-ft (~20-30 m) riparian buffers adjacent to mid-sized fish-bearing streams (Gregory 1997). Approximately 77% of the total number of 50-m tall trees expected to fall into the stream based on random fall directions originate within 30 m upslope from the

channel. Under directional fall on slopes > 90%, 71% of the total number 50-m tall trees expected to fall into the stream originate within 30 m of the channel (Fig. 7B). To equal the cumulative percent at 30 m from a random fall regime, a buffer on slopes > 90% would need to be 33 m wide. This indicates that second- to fourth-order stream reaches in steep-sided valleys receive a slightly greater percentage of wood from farther away from the channel than those in broad (alluvial) valleys. This supports findings from a study of small streams in southeast Alaska (Murphy and Koski 1989). Between 46-64% of in-stream wood originated from lower banks on alluvial reaches whereas only 19-23% came from these landforms on bedrock (constrained) sections (Murphy and Koski 1989). More importantly, this suggests that buffers designed for wood recruitment based on random fall directions adequately covers source distance of wood to streams with extremely steep side slopes. Riparian stands are composed of mixed height classes and side slope steepness is almost never constant upslope from the stream on both banks. Nonetheless, this modeling effort indicates that site potential for stream wood recruitment is influenced by side slope to the channel. The actual numbers of wood recruited from forests on steep side slopes in a highly constrained valley may be lower than our indications because of a greater chance to wedge above the stream channel (personal observation). Also, breakage of trees on impact with ground or stream surfaces is not considered (but see Chapter 3).

Current riparian management regulations for restoring and sustaining wood delivery to streams in the Pacific Northwest are largely based on random

tree fall directions (e.g., Oregon Department of Forestry 1994). At the majority of our sites (74%), directional fall was observed (Table 3). Thus, use of random fall directions to predict recruitment at these sites could under-predict the number of trees falling into the stream by up to three times. In either random fall or directional fall cases, the fall process is probabilistic rather than deterministic (Van Sickle and Gregory 1990). There is always a chance that a riparian tree will not fall into the stream even under conditions where tree fall tends most strongly towards the channel (i.e., slopes > 90%). Objectives for stream wood recruitment plans need to be carefully evaluated to formulate proper management strategies. If sustained wood recruitment from chronic riparian forest mortality is the primary objective, use of stream wood recruitment models that couple stand dynamics and tree fall is appropriate. However, if restoration of wood to a channel with inadequate levels is the primary goal, then active placement of pieces capable of forming pooling and/or retaining smaller may be necessary in addition to riparian forest management based on modeling efforts (as an example of active placement, see Gregory and Wildman 1994). Also, stochastic events may increase or decrease wood loading to individual sites over short periods of time (Benda and Sias 1998).

The primary finding from this research is that riparian tree fall directionality changed significantly with stream valley topographic features. On average, trees fell towards channels regardless of tree species, tree size, forest structure, rooting position away from the channel and side slope to the

channel. But, average fall directions do not adequately describe the patterns of riparian tree fall. Variance of tree fall directions declined with greater side slope steepness to the channel and between valley bottoms and hillslopes. Overall, directional fall based on slope steepness may supply 1.6 to 2.5 times more trees falling into a stream compared with random fall (Fig. 7A). Models of wood recruitment to streams should include a probabilistic function that describes the central tendency of falling towards the channel and the associated variance. Many models already have this structure in representation of tree fall (Van Sickle and Gregory 1990; Beechie et al. 2000; Meleason 2001). All that is needed is to replace the uniform random fall probability density function (pdf) with a normal pdf (mean and variance) and adjust fall direction mean and standard deviation according to slope steepness, rooting position and possibly by species type (eq. 3). Though stream wood recruitment is dynamic, our research findings on patterns of riparian tree fall should add greater accuracy to simulations of long-term wood delivery to streams from chronic mortality in riparian forests.

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Chapter 3

Tree fall breakage in streams and riparian zones in the Pacific Northwest

Daniel J. Sobota

ABSTRACT

Breakage of falling trees on impact with riparian and stream surfaces (fall breakage) is one of the least understood processes that directly controls number of pieces and size distribution of wood in forested streams. In this study, we quantified fall breakage along 21 second- to fourth-order streams throughout the Pacific Northwest, USA. Over half (58%) of down trees measured had not broken when they fell. Of those that did break, 52% (Interior Columbia Basin sites) to 78% (West of the Cascades Crest sites) of all breaks were not attributable to physical factors such as slope breaks between geomorphic landforms, underlying logs, rocks outcrops or channel margins. Across sites, percent of trees with falls break increased with tree height ($p < 0.0001$). Percent of breakage was similar among most species except for western larch, which had the highest percent of trees with breaks ($p < 0.0001$). Trees that broke typically produced 2 to 3 pieces per tree (20-50% coefficient of variation) with the first break occurring at half tree height (± 0.24 standard deviation; proportion relative to tree height). Trends in pieces per tree and location of first break either were statistically or ecologically insignificant along gradients of tree size and physical factors. With a simple model based on our field data, we demonstrate that fall breakage may amplify abundance of wood in streams by 1.1 to 1.8 times while at the same time reduce frequency of channel-spanning wood by 7 to 79%.

INTRODUCTION

Wood strongly influences ecology of streams in forested regions (Harmon et al. 1986). This allochthonous organic material reduces movement rates of sediments and fine organic materials, augments channel complexity and contributes large amounts of carbon and other essential nutrients for ecosystem-level processing in streams (Bisson et al. 1987; Bilby et al. 1999; Naiman et al. 2000). Over the past two decades, several simulation models have been developed for land managers to use in evaluating strategies for restoring and sustaining wood delivery to streams over time (e.g., Rainville et al., 1986; Van Sickle and Gregory 1990; Beechie et al. 2000; Bragg et al. 2000; Meleason 2001; Welty et al. 2001). Though these models provide strong tools for investigating relative effects of forest practices on volume of wood delivered to streams over time, predictions of piece numbers and size class distributions frequently are significantly different from field observations (e.g., Van Sickle and Gregory 1990).

Geomorphic and biological functional status of wood in channels is strongly influenced by piece length (Harmon et al. 1986; Bilby and Ward 1989). In forested streams < 20 m wide, pieces as long or longer than width of the active channel have greater stability and thus have higher probability to form pools and logjams (Lienkaemper and Swanson 1987; Bilby and Ward 1989). Pieces shorter than the width of the channel are highly mobile,

comprising 90-100% of pieces that redistribute throughout channel networks (Lienkaemper and Swanson 1987; Nakamura and Swanson 1994; Martin and Benda 2001). Length frequency distributions follow lognormal or reverse J-shaped distributions in streams with shortest length classes most frequent (Harmon et al. 1986). Little empirical data have been collected on processes that create and maintain piece numbers and length distributions in channels (Bragg et al. 2000; Meleason 2001). This lack of information compromises ability to accurately simulate abundance, stability and functional roles of wood in streams over time.

Breakage by falling trees on impact (fall breakage) is one of the least understood processes that directly controls number of pieces and length distribution of wood entering streams (Meleason 2001). In a comparison of simulation results to field data in a 10-m wide stream flowing through 500-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.) forest in the central Oregon Cascades, pieces > 10 m long were overestimated by almost 100% while pieces < 5 m long were underestimated by 80% (Van Sickle and Gregory 1990). An inaccurate fall breakage function was attributed to this difference. Several recent models have incorporated stratified random breakage (Meleason 2001) or breakage patterns based on fragmentation of dead standing trees (Bragg et al. 2000). Influential factors on the process are not considered. Species type, tree size and topography have all been indicated to influence probability of fall breakage (Rapraeger 1932; Snell and

Brown 1980; Hunt and Henley 1981; Murphy 1984; Lienkaemper and Swanson 1987). Few studies have examined the number and length distribution of pieces produced from fall or felling practices (Murphy 1984) and fewer still have examined patterns in streams and riparian areas (Lienkaemper and Swanson 1987). Existing studies have limited scope of inference because of low numbers (< 30 trees) and small spatial scales of observations.

This research provides the first extensive empirical data on patterns of natural fall breakage (unrelated to felling practices) in riparian areas and streams. Surveys of down riparian trees were conducted at second- to fourth-order stream sites in several forest age classes and physiographic regions of the Pacific Northwest. We answer four basic questions to describe patterns of breakage by trees falling into stream channels and riparian areas:

- (1) When a riparian tree falls, does it break on impact?
- (2) If a riparian tree breaks on fall impact, how many pieces are produced and where do breaks occur on the bole?
- (3) Do percent and patterns of fall breakage vary among species, tree size or topographic/stream geomorphic conditions?
- (4) How do probability and patterns of fall breakage potentially influence numbers and length distribution of wood entering stream channels?

SITE DESCRIPTIONS

Twenty-one second- to fourth-order streams were surveyed from west of the Cascades crest (11 sites; hereafter referred to as WCC) and the Interior Columbia Basin (10 sites; hereafter referred to as ICB) of the Pacific Northwest, USA (Table 5). Private timber companies and the USDA Forest Service provided study streams. Locations of study sites were selected randomly. Study sites were 200 to 300 m in stream length and 50 m upslope ground distance on one or both stream banks. Active channel widths ranged from 2.5 to 14.0 m wide, valley constraints ranged from 1.4 to 25.7 and forest ages ranged from 40-500 years old (Table 5).

Table 5. Selected physical characteristics and riparian forest age of study sites in the Pacific Northwest, USA. Coefficients of variation (%) are in parentheses where applicable.

Stream	Active channel width (m)	Valley constraint	Valley side slope (%)	Forest age (years)
<u>Interior Columbia Basin</u>				
N.F. Cabin Creek, OR	4.1 (24)	25.7	12 (94)	40
S.F. Cabin Creek, OR	4.4 (18)	15.1	13 (134)	40
Piper Creek, MT ¹	9.3 (26)	2.5	28 (86)	50
Bloom Creek, ID	3.4 (27)	11.3	45 (49)	50
Murr Creek, MT	5.4 (31)	2.9	33 (59)	90
Big Creek, WA	13.0 (21)	2.0	62 (40)	150
Little Creek, WA	7.0 (14)	2.1	62 (54)	150
Squeezer Creek, MT	11.5 (29)	2.2	33 (77)	200
W.F. Mica Creek, ID	2.5 (44)	9.6	35 (49)	>200
Goat Creek, MT	8.0 (34)	2.3	40 (56)	200
<u>West of Cascades crest</u>				
Sturdy Creek, OR	11.8 (23)	2.3	30 (97)	40
Forks Creek, WA	12.8 (4)	2.3	20 (90)	40
N.F. Gate Creek, OR	11.4 (16)	1.9	31 (86)	50
Green Canyon Creek, WA	8.7 (20)	3.4	29 (79)	60
Stillman Creek, WA	4.4 (33)	3.5	36 (62)	60
Crim Creek, WA	10.5 (10)	1.2	46 (50)	80
Hagan Creek, OR	11.3 (25)	3.3	49 (60)	110
McCain Creek, WA	10.6 (39)	6.9	40 (65)	120
Flynn Creek, OR	11.9 (27)	2.4	51 (63)	170
Cedar Creek, OR	11.6 (14)	1.3	23 (103)	500
Mack Creek, OR	9.2 (34)	2.5	68 (48)	500
Overall:	8.7 (28)	5.1 (31)	40 (72)	--

¹Western redcedar on one terrace were ~200 years old

METHODS

We conducted exhaustive inventories of down riparian trees to record as many trees as possible per site to increase statistical power of analyses. Minimum tree size dimensions were a 10-cm diameter at breast height (dbh) and a 5-m height. Surveys proceeded upstream from start points of sites until 100 trees or the entire site area was sampled (~half of measured trees on each bank). For each down riparian tree, we recorded whether it had broken at time of fall; for those with fall breaks we counted the number of pieces (only from fall breakage) and specifically measured location of breaks relative to tree bole (from base to tip). Perpendicular breaks relative to the bole were the most common break type from field observations. We also noted probable cause of a fall break if a physical factor could be attributed (i.e., slope break between geomorphic landforms, active channel margins, underlying rocks, down logs, other (live trees, stems, etc.), and ground impact). Breaks resulting from impact of other falling trees, decomposition and other processes occurring after tree fall were not considered in analysis of fall breakage.

In addition to fall breakage patterns, we recorded species type and size dimensions of individual trees and physical characteristics of rooting position. Species, tree size (dbh and tree height) and whether the tree was root-thrown or stem-broken (as an indicator of whether the tree was alive or dead at time of fall) were recorded for each tree. For rooting position characteristics, we

recorded side slope (%; $\text{m}\cdot\text{m}^{-1}$) to the stream channel and ground distance of the tree base to the margin of the active channel. Species were determined from bark morphology, branch structure and leaf or needle characteristics if present (Harlow and Harrar 1968). Tree dbh was measured by standard methods using dbh-corrected tapes (Avery and Burkhart 1994). Tree height was measured to provide conservative estimates of height at time of fall. Trees spanning streams with missing pieces in the channel were measured from the base to the end of the piece on the far side assuming the gap missing from the channel was the missing piece length (and resulted from a fall break). Side slope to the stream channel was measured on the geomorphic landform where the tree rooted with a clinometer. Ground distance of the tree base to the margin of the active channel was recorded with tapes or a Bushnell[®] 500 Laser Range Finder depending on tree proximity to the channel and topographic roughness.

For all statistical analyses, α was set to the 5% level. We summarized percent and patterns of fall breakage by site (Table 2). A binary code represented whether the tree had experienced fall breakage (1) or not (0). We also analyzed number of breaks and location of first break relative to total height of the tree bole. Before beginning analyses, tree species that constituted < 1% of total number of down trees measured across sites and unidentified species were removed from our data matrix. The maximum number of trees removed from one site was 20 trees out of 100 for Goat

Creek, MT. These trees consisted of paper birch (*Betula papyrifera* Marsh.), Rocky Mountain maple (*Acer glabrum* Torr.) and several unidentified trees. We also removed data from N.F. and S.F. Cabin Creeks, OR, from statistical analyses out of concern for their disproportionately small sample sizes compared with other sites.

Trees were pooled across sites to identify frequencies of fall breakage causes and to construct models of breakage patterns as a function of individual tree characteristics and rooting position variables. Interaction terms among tree height, dbh and side slope were not included in models. Tree size characteristics did not vary strongly by side slope. Median dbh increased by 0.6 to 3.0% (95% confidence interval (CI)) while median tree height increased by 0.1 to 2.0% for every increase in side slope of 10% ($p=0.006$ and 0.03 , respectively; $r^2<0.01$ and 1093 d.f. each).

Regression models do not always perform strongly when used to predict independent data sets (Montgomery et al. 2001). The observational design of the current study only allows identification of correlations with measured environmental variables; causal relationships cannot be formally determined. To provide a critical understanding of the predictive capabilities of the multiple logistic regression model that we constructed to predict probability of breakage, we used a validation procedure to assess model accuracy (Montgomery et al. 2001). We randomly removed 25% of our field data to provide a database to validate a test multiple logistic model (Ramsey and

Schafer 1997; Montgomery et al. 2001). Probability of fall breakage was modeled as a function of tree height (natural log), dbh (natural log), fall type, side slope and species. Significant explanatory variables were determined with drop-in-deviance χ^2 -tests (Ramsey and Schafer 1997). After model construction, we used the remaining 25% of data to assess model accuracy for each species by constructing a cross tabulation table. A predicted probability < 0.5 indicated no break and > 0.5 indicated a break (Tabachnick and Fidell 2001). Following evaluation, we reconstructed the model with the full data set to improve precision of coefficient estimates (Montgomery et al. 2001).

For trees that broke when they fell, we assumed that number of pieces produced followed a Poisson distribution because data were counts of pieces and initial screening indicated that variance increased on gradients of all explanatory variables. Poisson (log-linear) regression techniques were used to assess pieces per tree as a function of tree characteristics and rooting position. Significant variables were selected through deviance goodness-of-fit χ^2 -tests (Ramsey and Schafer 1997).

Proportion of tree height to first break was modeled as a function of tree size and rooting position characteristics with multiple linear regression techniques. Significant explanatory variables were determined with the backwards selection process of extra-sums-of-squares F -tests (Ramsey and Schafer 1997). Two to nine breaks were observed among all trees. We did

not analyze location of breaks beyond the first on broken trees because the sample size decreased rapidly with each sequential increase in break number and variation of location of breaks (relative to tree height) were extremely variable (standard deviation (SD) of proportion of height to break > 0.20). All statistical analyses were conducted with S-Plus 2000 (MathSoft, Inc.; Seattle, WA).

RESULTS

FIELD RESULTS

Overall, 462 of 1095 riparian trees (42%) surveyed across all sites broke when they fell (excluding N.F. and S.F. Cabin Creeks). Percent of down trees with fall breaks by site ranged from 19 to 63% (Table 6). In pooling trees across sites, numbers of pieces per tree had a right-tailed skewed distribution (geometric mean of 2.7 with 42% coefficient of variation (CV)) while proportion of tree height to first break had a normal distribution ($p=0.21$; Kolmogorov-Smirnov goodness-of-fit test; 1093 d.f.) centered on 0.50 (± 0.24 SD) (Table 6).

A total of 979 fall breaks were recorded on the 462 down trees that had broken. We identified 431 breaks on 557 down riparian trees surveyed on WCC sites and 548 breaks on 538 riparian trees measured on ICB sites. Majority of breaks in both regions resulted from surface impact or from causes that we could not clearly identify (52% on ICB sites, 78% on WCC sites and 62% overall) (Fig. 8). Impact with underlying logs (16% overall), fall across slope breaks (12% overall), other/impact with live trees or stems (6% overall), intersection with the channel (3% overall), and impact on rocks or boulders (1% overall) comprised the remaining identifiable break causes (Fig. 8).

Trees from older forests had a slightly greater percent of trees that experienced fall breakage than younger forests ($p=0.08$; $F=3.5$; 1, 17 d.f.) (Fig. 9). Percent of trees with fall breaks slightly increased from 31% in 40-year-old stands to 52% in 500-year-old stands. On average, percent of trees with fall breaks increased by 4.5% for every doubling of forest age (95% confidence interval (CI) -1.4 to 10.1%). In this model, forest age was transformed to natural logs to reduce leverage influence (0.42 each) of the two 500-year-old stands; N.F. and S.F. Cabin Creeks were not included because of small sample sizes (Fig. 9). Percent breakage did not change with site-level variables describing physical characteristics (active channel width, valley constraint and average side slope steepness to the channel) and did not significantly differ among regions ($p>0.22$; $F<1.67$; 2-6, 12-16 d.f.; backwards variable selection using extra-sum-of-squares F -tests).

Table 6. Fall breakage patterns of riparian trees at study sites in the Pacific Northwest, USA.

Stream	Trees (<i>n</i>)	Trees with break (%)	Of trees that broke:	
			Pieces per tree ¹	Height proportion to first break ²
<u>Interior Columbia Basin</u>				
N.F. Cabin Creek, OR ³	16	19	2.0 (0)	0.37 (0.27)
S.F. Cabin Creek, OR ³	10	30	2.0 (0)	0.73 (0.41)
Piper Creek, MT	94	49	3.4 (50)	0.54 (0.31)
Bloom Creek, ID	50	40	2.7 (38)	0.53 (0.23)
Murr Creek, MT	99	19	2.2 (18)	0.75 (0.25)
Big Creek, WA	57	39	2.8 (34)	0.59 (0.37)
Little Creek, WA	43	53	2.9 (45)	0.42 (0.29)
Squeezer Creek, MT	88	52	2.6 (42)	0.50 (0.25)
W.F. Mica Creek, ID	46	35	2.3 (33)	0.43 (0.27)
Goat Creek, MT	80	56	3.0 (49)	0.55 (0.31)
<u>West of Cascades crest</u>				
Sturdy Creek, OR	24	33	2.4 (32)	0.73 (0.26)
Forks Creek, WA	38	39	2.3 (21)	0.68 (0.35)
N.F. Gate Creek, OR	51	49	2.4 (37)	0.82 (0.29)
Green Canyon Creek, WA	47	42	2.3 (27)	0.60 (0.38)
Stillman Creek, WA	50	30	2.7 (42)	0.58 (0.29)
Crim Creek, WA	42	17	2.2 (28)	0.37 (0.23)
Hagan Creek, OR	26	35	2.2 (21)	0.85 (0.17)
McCain Creek, WA	50	56	2.6 (34)	0.64 (0.30)
Flynn Creek, OR	65	38	2.5 (32)	0.46 (0.29)
Cedar Creek, OR	49	63	3.2 (55)	0.50 (0.28)
Mack Creek, OR	96	46	2.7 (33)	0.39 (0.27)
Overall:	1095	42	2.7 (42)	0.50 (0.24)

¹Geometric mean (Coefficient of variation = %)

²Average (\pm SD)

³Not included in overall summary statistics

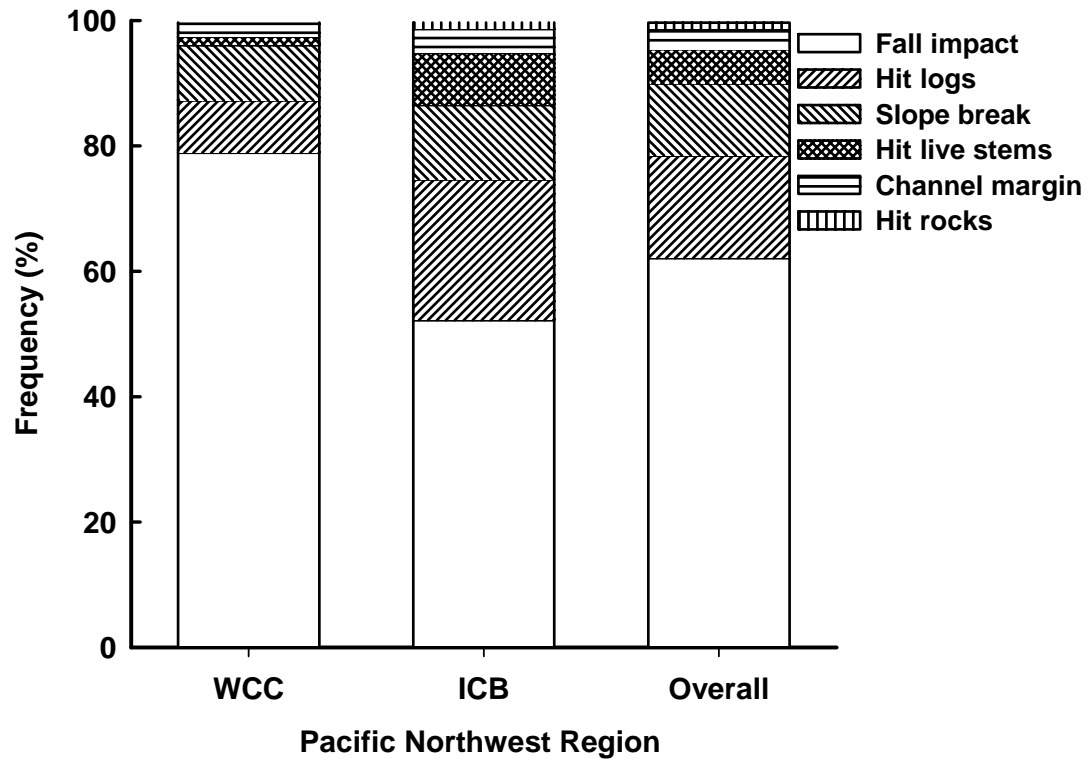


Fig. 8. Percent of fall breaks on riparian trees attributable to several physical and topographic features at study sites in the Pacific Northwest, USA. WCC = west of Cascades crest; ICB = Interior Columbia Basin.

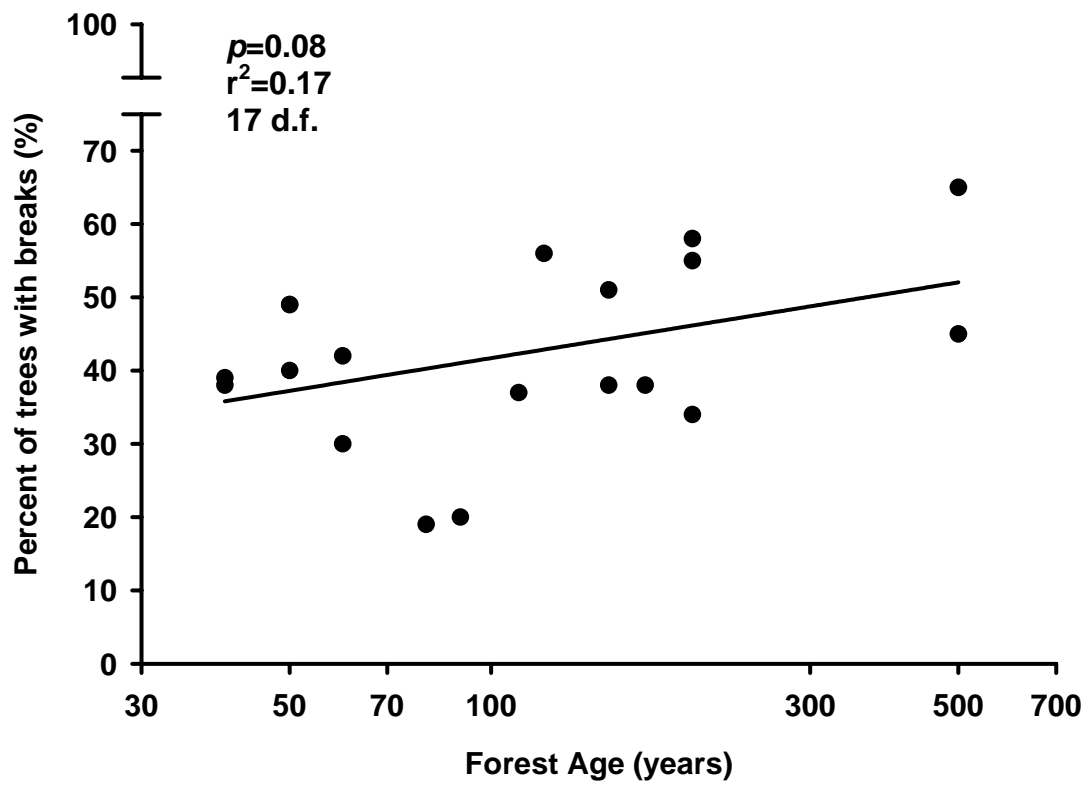


Fig. 9. Trees with fall breaks as a function of forest age at study sites in the Pacific Northwest, USA. Linear regression equation is: Percent of trees with breaks = $12.1 + 6.4 * \ln(\text{forest age})$.

Based on the test model built from 821 randomly selected trees from our original data set, probability of tree breakage increased with tree height, but rate of increase differed among species ($p < 0.0001$; multiple logistic regression model; drop-in-deviance=112.3; 17 d.f.). Variables for this model are listed in Table 7; Fig. 10 and Table 8 show this model after reconstruction with the full data set. Through evaluation of a full model including interactive effects of tree height and species, fall type (drop-in-deviance=4.2), natural log of dbh (drop-in-deviance=1.4), slope (drop-in-deviance=1.5) and distance from

the channel (drop-in-deviance=0.6) were not associated with probability of breakage ($p=0.10$; total drop-in-deviance=7.7; 4 d.f.).

Table 7. Validation of a multiple logistic model for probability of breakage by trees falling into streams and riparian zones in the Pacific Northwest, USA (with interactive effects of species and height). For the procedure, 75% of data were used to construct the model and 25% (n_p) were used assess model accuracy. A proportion of < 0.5 indicated no break and > 0.5 indicated a fall break. Standard errors are in parentheses. The model is:

$$\text{logit}(\text{probability of break}) = \beta_0 + \beta_1 * \ln(\text{height}) + \beta_2(\text{species indicator}) + \beta_3(\text{species indicator}) * \ln(\text{height})$$

where β_0 is -2.26 (2.83) and β_1 is 0.65 (1.11). See Fig. 10 for model constructed from full data set.

Species	β_2	β_3	n_p	Accuracy (correct predictions/ n_p)
Grand fir (reference)	0 (0)	0 (0)	9	0.89
Red alder	0.33 (2.97)	-0.07 (1.16)	31	0.55
Western larch	-3.19 (4.00)	1.54 (1.47)	13	0.69
Lodgepole pine	-9.92 (4.82)	3.20 (1.72)	11	0.64
Engleman spruce	-1.20 (3.20)	0.47 (1.23)	31	0.70
Douglas-fir (Interior)	-1.01 (3.12)	0.72 (1.22)	25	0.24
Douglas-fir (Coastal)	0.47 (2.91)	-0.07 (1.13)	70	0.54
Western redcedar	-3.49 (3.10)	1.11 (1.19)	49	0.65
Western hemlock	1.54 (3.11)	-0.30 (1.22)	32	0.41
Overall	--	--	274	0.56

Validating the model of species-height interactive effects on breakage with the 25% of randomly removed data showed that the test model predictive capability was only 56% accurate (Table 7). But, this may simply reflect lower

statistical power of the validation data set. Accuracy varied among species, ranging from 24% (Douglas-fir Interior) to 89% (grand fir). Further inspection of this model revealed that standard errors of coefficients for common and separate height coefficients for each species were extremely large (except for 2 cases, $SE > \text{coefficient value}$) (Table 8). Dropping the interactive effect between height (natural log) and species to produce a model with a common height coefficient but differences of breakage probabilities among species improved the precision of the intercept ($-3.06 \pm 0.58 \text{ SE}$) and the scaling coefficient for tree height ($0.96 \pm 0.13 \text{ SE}$) in a new test model (75% data) (Table 9) (model based on full data set is in Fig. 11 and Table 10). Using the same validating procedure as that for the test species-height interactive model, the model with a common height coefficient and differences among species was only 51% accurate when compared with the validation data set (25% of data) (Table 9). Furthermore, a test model with a height coefficient and no differences among species correctly predicted breakage in 61% of the trials of the validation data set (Table 11) (see Fig. 12 for model constructed with full data set).

To further strengthen precision of coefficients in the three models (species-height interactive effect, height effect with differences among species, and only height effect), we reconstructed them with our full data set (Fig. 10, 11 and 12). All three models indicate tree height was the most important variable for probability of fall breakage. In all three models, the

drop-in-deviance for the height coefficient was 55.2 (1 d.f.). The drop-in-deviance for the species differences was 35.7 (8 d.f.) while the drop-in-deviance for the species-specific height coefficient was 30.9 (8 d.f.). These statistics demonstrate that tree height was the most important variable for predicting probability of tree breakage.

Patterns of fall breakage were extremely variable across sites (Fig. 13 and 14). Number of pieces produced from fall breakage slightly increased with tree height ($p=0.005$; drop-in-deviance=7.6; 1 d.f.) (Fig. 13). Number of pieces produced from fall breakage increased by 2 to 18% (95% CI) for every doubling of tree height (Fig. 13). Evaluation of a full model including all possible explanatory variables indicated that fall type (drop-in-deviance=0.4), natural log of dbh (drop-in-deviance=0.1), slope (drop-in-deviance=0.1) distance from the stream (drop-in-deviance=0.1) and regional location (drop-in-deviance=0.7) were not associated with number of pieces produced during fall breakage ($p=0.92$; total drop-in-deviance=1.4; 5 d.f.). Also in this evaluation of model coefficients, species type was not associated with pieces generated from breakage ($p=0.35$; drop-in-deviance=8.9; 8 d.f.).

Weak trends in the proportion of tree height to first break were detected among trees that broke (Fig. 14). Using a backwards selection procedure with extra-sum-of-squares F -tests, proportion of height to first break was significantly associated with natural log of dbh ($F=4.1$), distance from the stream channel ($F=4.4$), and species type ($F=2.0$) ($p=0.007$; $F=2.4$; $r^2=0.05$;

10, 451 d.f.). But, the low variance explained indicates that the model had little predictive value. Using backwards selection extra-sum-of-squares F -tests, first break location was not significantly associated with tree height ($F=1.4$), side slope steepness ($F=0.4$), distance from the stream ($F=0.$), fall type ($F=0.2$) or regional location ($F=0.99$) (overall; $p=0.30$; total $F=1.9$; 4 d.f.).

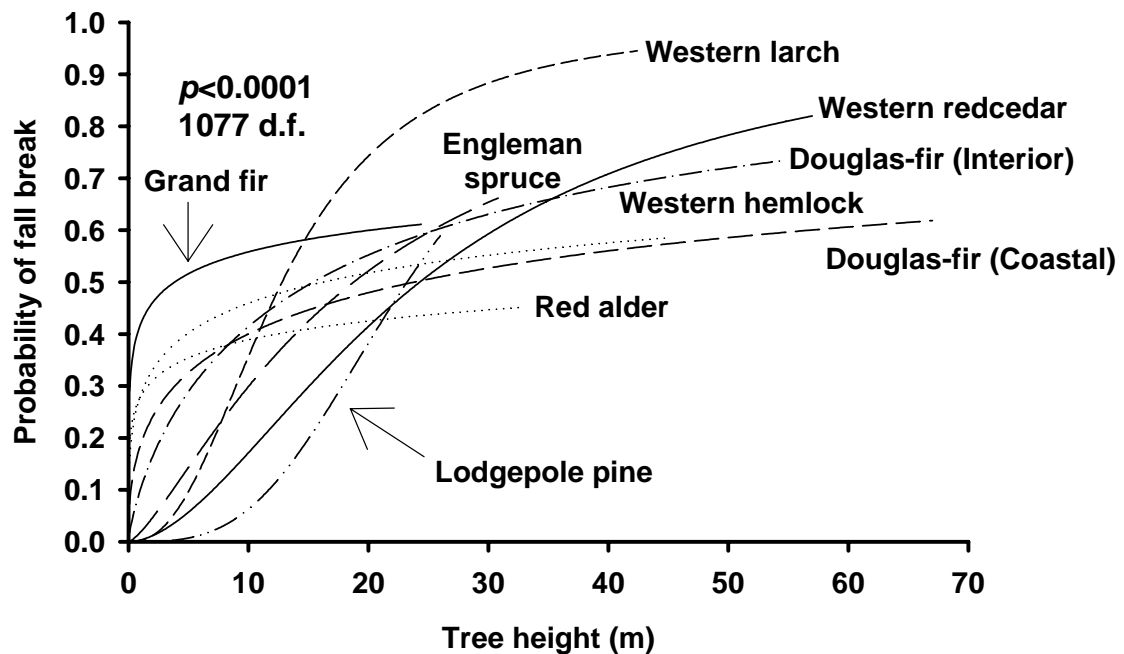


Fig. 10. Model predictions of probability that a riparian tree broke on fall as a function of an interaction between species and tree height at study sites in the Pacific Northwest, USA (constructed with full data set). Lines extend to maximum tree heights by species in this study. The model is:

$$\text{logit}(\text{probability of breakage}) = \beta_0 - \beta_1 * \ln(\text{height}) + \beta_2(\text{species indicator}) + \beta_3(\text{species indicator}) * \ln(\text{height})$$

See Table 8 for the regression coefficients ($\beta_0, \beta_1, \beta_2, \beta_3$).

Table 8. Coefficients of the multiple logistic regression model presented in Table 7, after refitting with the full data set. See Fig. 10 for graphical display. Standard errors are in parentheses for coefficients. $\beta_0 = -0.33$ (2.37) and $\beta_1 = 0.62$ (0.94). Note that β_1 is -0.62 for grand fir. Coefficients for differences among species (β_2) and species-specific height coefficients (β_3) are listed below.

Species	β_2	β_3
Grand fir (reference)	0 (0)	0 (0)
Red alder	-0.62 (2.48)	0.46 (0.99)
Western larch	-5.74 (3.42)	2.62 (1.26)
Lodgepole pine	-9.75 (3.79)	3.45 (1.38)
Engleman spruce	-3.65 (2.69)	1.60 (1.04)
Douglas-fir (Interior)	-1.86 (2.60)	1.05 (1.03)
Douglas-fir (Coastal)	-1.15 (2.44)	0.71 (0.96)
Western redcedar	-5.34 (2.59)	2.02 (1.01)
Western hemlock	-0.61 (2.59)	0.58 (1.03)

Table 9. Validation of the multiple logistic model for probability of breakage by riparian trees in the Pacific Northwest, USA (species differences). For the procedure, 75% of data were used to construct the model and 25% (n_p) was used validate. A proportion of < 0.5 indicated no break and > 0.5 indicated a fall break. Standard errors are in parentheses. The model is:

$$\text{logit}(\text{probability of break}) = \beta_0 + \beta_1 * \ln(\text{height}) + \beta_2(\text{species indicator})$$

where β_0 is -3.06 (0.58) and β_1 is 0.97 (0.15). See Fig. 11 and Table 10 for graphical display and coefficients of the model after reconstruction with the full data.

Species	β_2	n_p	Accuracy (correct predictions/ n_p)
Grand fir (reference)	0 (0)	9	0.89
Red alder	0.16 (0.48)	31	0.32
Western larch	1.21 (0.47)	13	0.76
Lodgepole pine	-0.81 (0.56)	11	0.55
Engleman spruce	0.03 (0.50)	31	0.70
Douglas-fir (Interior)	0.77 (0.50)	25	0.24
Douglas-fir (Coastal)	0.18 (0.47)	70	0.53
Western redcedar	-0.46 (0.49)	49	0.59
Western hemlock	0.80 (0.51)	32	0.41
Overall	--	274	0.51

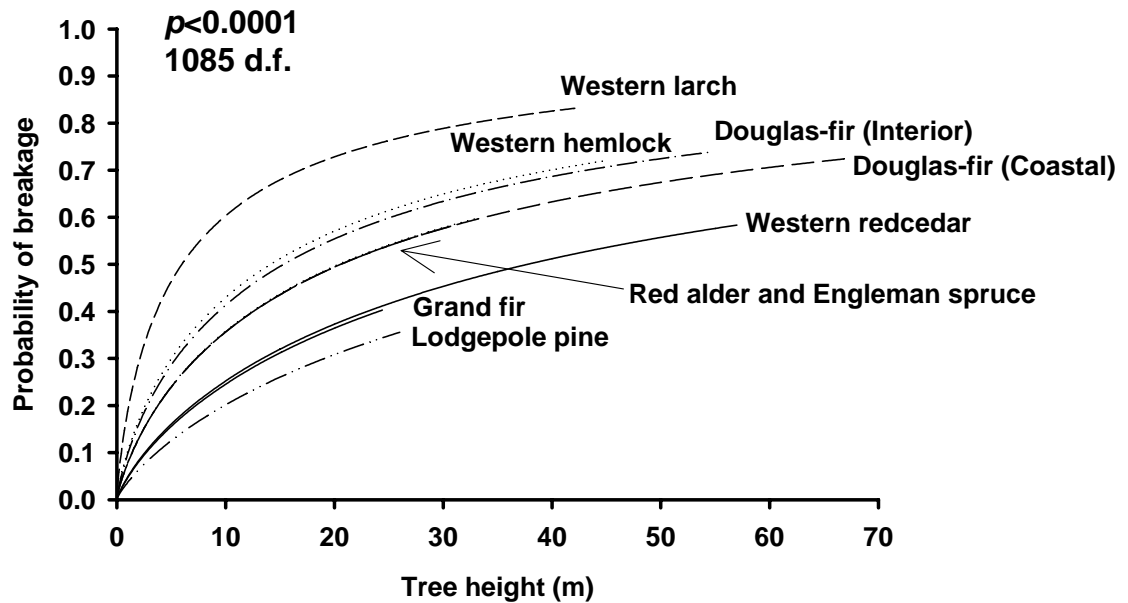


Fig. 11. Model predictions of the probability that a riparian tree broke on fall as a function of tree height with linear combinations of differences among species along study sites in the Pacific Northwest, USA (constructed with full data set). Lines extend to maximum tree heights by species in this study. The model is:

$$\text{logit}(\text{probability of breakage}) = \beta_0 + \beta_1 * \ln(\text{height}) + \beta_2(\text{species indicator})$$

See Table 10 for the regression coefficients (β_0 , β_1 , β_2).

Table 10. Coefficients for the multiple logistic regression model presented in Table 9, after refitting with the full data set. Standard errors are in parentheses. See Fig. 11 for graphical display. Standard errors are in parentheses for coefficients. $\beta_0 = -3.01 (0.51)$ and $\beta_1 = 0.82 (0.12)$. Coefficients for differences among species (β_2) are listed below.

Species	β_2
Grand fir (reference)	0 (0)
Red alder	0.54 (0.43)
Western larch	1.54 (0.50)
Lodgepole pine	-0.25 (0.49)
Engleman spruce	0.53 (0.44)
Douglas-fir (Interior)	0.77 (0.44)
Douglas-fir (Coastal)	0.53 (0.42)
Western redcedar	0.04 (0.43)
Western hemlock	0.84 (0.45)

Table 11. Validation of a multiple logistic model for probability of breakage by trees falling into streams and riparian areas in the Pacific Northwest, USA (only height as a predictor). For the procedure, 75% of data were used to construct the model and 25% (n_p) were used validate. A proportion of <0.5 indicated no break and >0.5 indicated a fall break. Standard errors are in parentheses. The model is:

$$\text{logit}(\text{probability of break}) = \beta_0 + \beta_1 * \ln(\text{height})$$

where β_0 is -2.79 (0.38) and β_1 is 0.92 (0.14). See Fig. 12 for graphical display and coefficients of the model reconstructed from the full data set.

Species	n_p	Accuracy (correct predictions/ n_p)
Grand fir	9	0.78
Red alder	31	0.29
Western larch	13	0.77
Lodgepole pine	11	0.64
Engleman spruce	31	0.64
Douglas-fir (Interior)	25	0.80
Douglas-fir (Coastal)	70	0.54
Western redcedar	49	0.69
Western hemlock	32	0.66
Overall	274	0.61

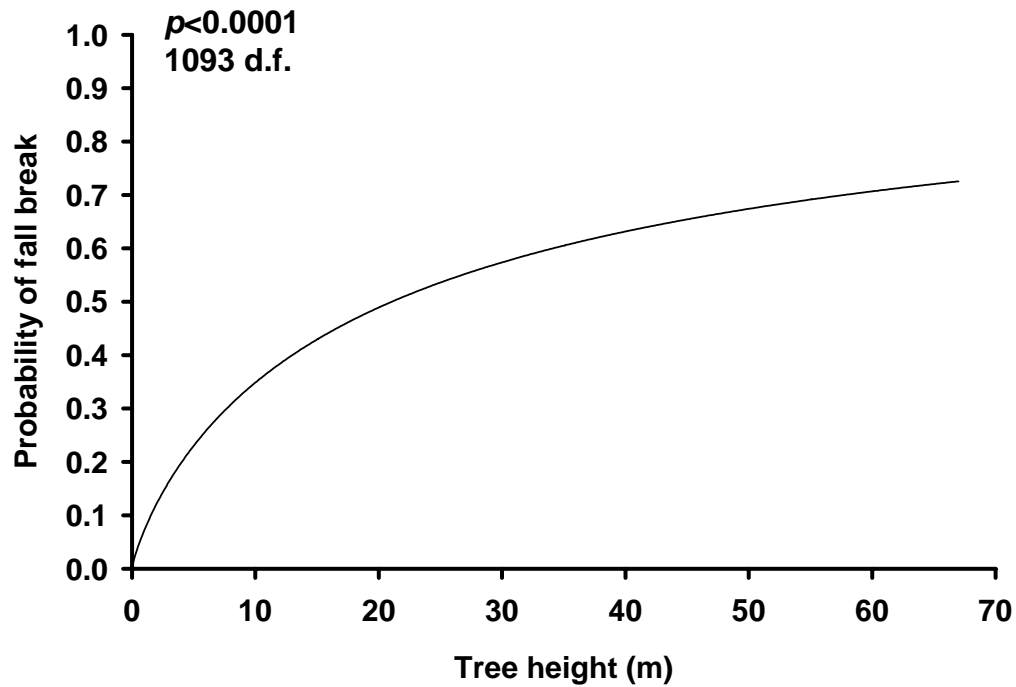


Fig. 12. Model prediction of probability that a riparian tree broke as a function of tree height at study sites in the Pacific Northwest, USA (constructed from full data set). Line extends to maximum tree height in this study. Standard errors are in parentheses. The model is:

$$\text{logit}(\text{probability of breakage}) = -2.56 + 0.84 * \ln(\text{height})$$

where β_0 is -2.56 (0.32) and β_1 is 0.84 (0.12).

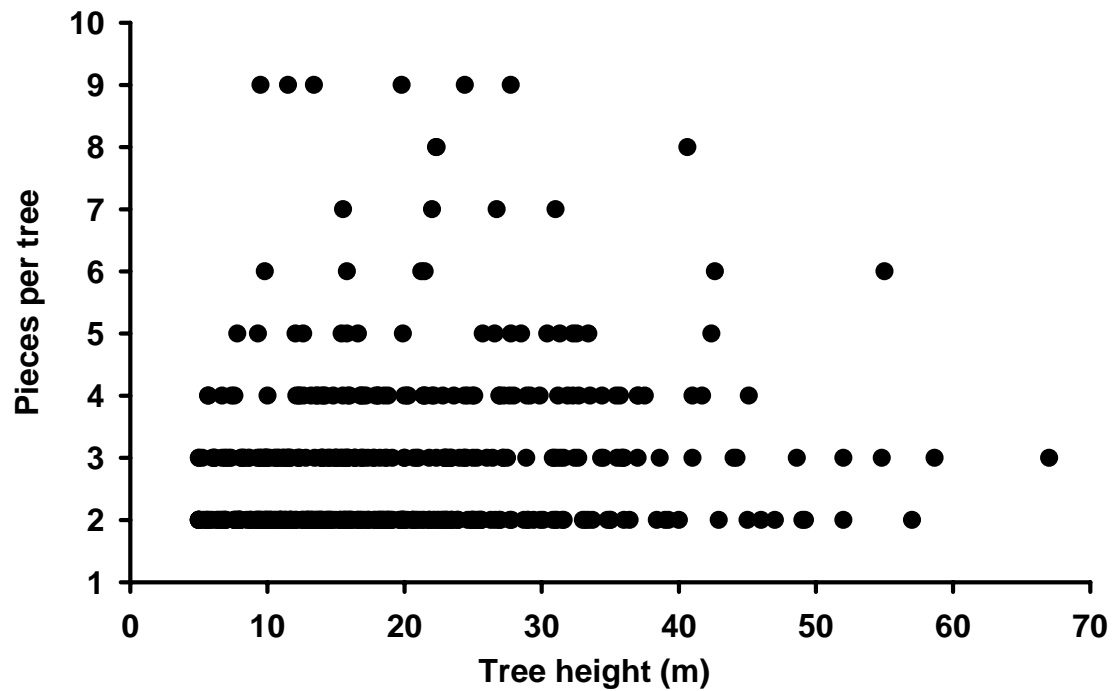


Fig. 13. For riparian trees that broke, number of pieces produced as a function of tree height at study sites in the Pacific Northwest, USA. Poisson (log-linear) regression equation is $\ln(\text{number of pieces}) = 0.68 + 0.14 * \ln(\text{tree height})$; $p=0.005$ with 460 d.f.

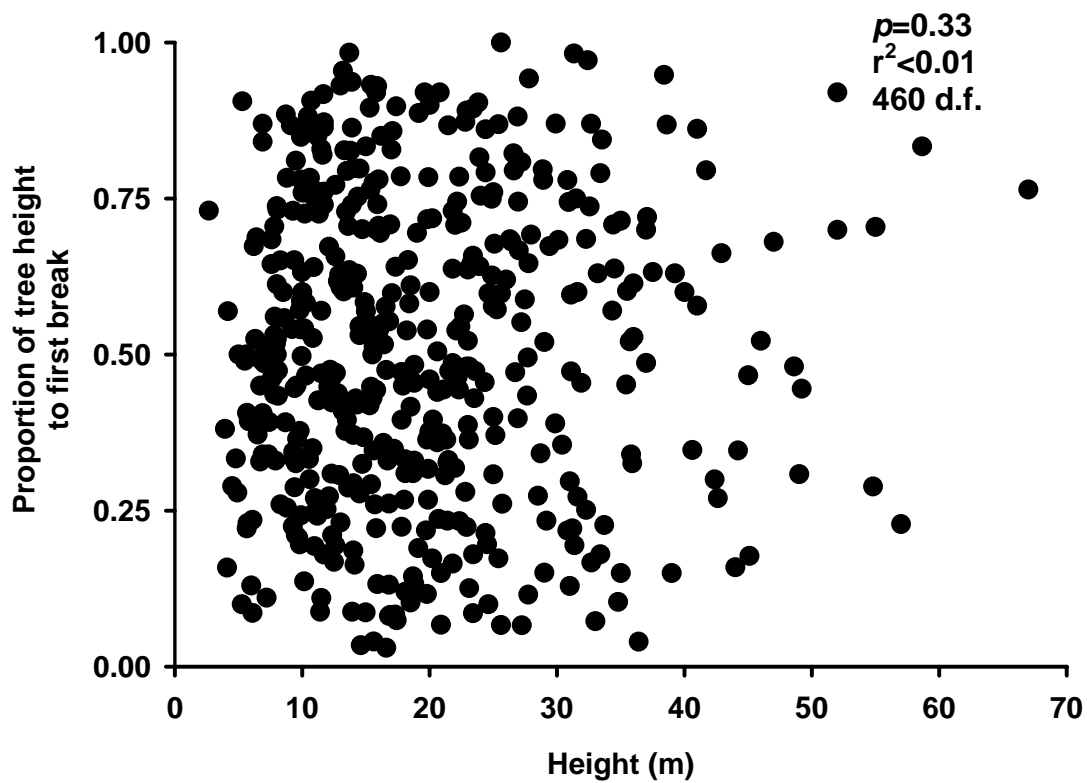


Fig. 14. For riparian trees that broke, proportion of tree height to first break as a function of tree height among study sites in the Pacific Northwest, USA.

FALL BREAKAGE MODEL

Breakage by riparian trees on impact with stream channels and riparian zones may have a strong effect on the size distribution of wood entering streams. Excluding a function for fall breakage in wood recruitment modeling can result in an over-prediction of length class and volume per piece frequency distribution entering streams (Van Sickle and Gregory 1990). Because large pieces of wood (longer than the active channel) have strong geomorphic influences in streams (Bilby and Ward 1989), inflated estimates of wood size distribution may lead to erroneous conclusions on future abundance of fish habitat, channel structure and organic matter retention by streams under various riparian management scenarios.

Three functions must be modeled to properly estimate breakage by riparian trees on impact with streams and riparian zones: (1) probability that a tree breaks when it falls, (2) number of pieces produced if a tree breaks and (3) location of breaks on the bole. Multiplying pieces per tree by the number of trees falling into a stream is not an appropriate representation of fall breakage. This method will over-predict stream wood abundance and does not describe length distribution. Probability of breakage and locations of breaks are critical for estimating spatial distribution and length frequency of wood entering streams. If a tree does not break, the height of the tree is translated to the length of the in-stream wood piece. Breaks that occur on the bole outside of

the channel do not alter in-stream wood numbers or size distribution. Thus, effects of fall breakage are spatially explicit and depend on rooting distance from the stream and size dimensions of the tree.

To explore these effects, we simulated number of pieces and overall length distribution of pieces entering a stream for a 100-year time period. Dimensions of the model system were a 10-m wide channel, a 200-m long reach and a 30-m buffer upslope on both banks. The width of this buffer is typical of medium-sized, fish-bearing streams on private and state forestlands in the Pacific Northwest (Gregory 1997; Young 2000). For simplicity, trees were assumed to stand at the midpoints of 10-m upslope sections in the buffer (5, 15 and 25 m upslope). Trees heights were defined by 5-m intervals beginning with 15 m (shortest possible height for a channel spanning piece at 5 m upslope) up to 50 m. For trees 15, 20 and 25 m tall, we assumed three trees per height class would fall per century from both stream banks and in each 10-m interval upslope. Two trees in each height class of 30, 35, 40, 45 and 50 m were assumed to fall per century from both stream banks and in each 10-m interval upslope. These fall rates are slightly higher than field observations from a 500-year-old Douglas-fir forest stream in the Oregon Cascades (probability of fall 0.8 to 4% relative to density per century) (Van Sickle and Gregory 1990) and were set to facilitate ease of interpretation. Species were not distinguished because only western larch had significantly different breakage patterns in field data. Trees were assumed to fall

completely towards the stream. We recognize that tree fall direction is probabilistic; assuming complete towards channel fall allows us to evaluate the maximum effect of fall breakage on abundance and size distribution of wood entering channels. Finally, we did not consider geomorphic or topographic conditions of the model system because our field data did not show statistically or ecologically significant relationships with physical aspects of the stream valley. Wedging between stream banks may be a significant occurrence in constrained valleys (personal observation) but also is not considered in this effort.

We evaluated effects of fall breakage on length frequency and number of wood pieces entering channels with four scenarios (no breakage, low breakage, average breakage and high breakage). Low, average and high breakage scenarios were based on means \pm one standard deviation of field data (for pieces per tree; geometric mean and coefficient of variation) (Table 6). Number of trees that broke at least once for each scenario was approximated by assuming probability of breakage increased with tree height (except no breakage scenario) (Table 12) (Fig. 12). Each breakage scenario had distinct breakage patterns for trees that broke on impact (Table 12).

In the low breakage scenario, one tree broke in the 15, 20, 25, 45 and 50 m height classes (Table 12). We did not break trees in the 30, 35 and 40 m height class at any distance upslope from the stream (Table 12). For trees that did break, they broke once and location of first break occurred at three-

fourths overall tree height. This scenario provided the most conservative effects of fall breakage on piece numbers and length distribution.

For the average breakage scenario, one tree was broken out of the three that fell in the 15, 20, 25 and 30 m height classes (Table 12). One of the two falling trees in each of the 35, 40, 45 and 50 m classes broke upon entering the channel (Table 12). We assumed that trees would break twice and occur at half the length of the breaking piece (Table 6 and 12). These locations represent the average and typical deviation from the average among all trees across sites. The second break location was half the length of the piece produced from the first break.

The high breakage scenario provided the most liberal estimates of effects of fall breakage on stream wood size distribution and numbers. Two out of the three falling trees were broken in the 15, 20, 25 and 30 m height classes (Table 12). All of the falling trees in each of the 35, 40, 45 and 50 m height class broke. All broken trees produced five pieces. The first break occurred at one-fourth height while break locations beyond the first were sequentially halved relative to the length of the piece to be broken (Table 12).

In all scenarios, a piece was removed from the stream wood population if it existed outside of the stream channel. Pieces were removed from if the resulting piece was < 1 m in length. If touching the channel, the entire length of a wood piece was considered in length frequency distributions. We did not consider diameter in these scenarios.

Table 12. Parameters of a model for fall breakage of trees falling into a 10-m wide stream over a 200-m long reach. For all scenarios, trees fell directly towards the stream.

Parameters	Low Breakage	Average Breakage	High Breakage
Probability of break (15-25 m tall) (%)	19-24	31-41	48-61
Model trees with break (15-25 m tall)	1	1	2
Probability of break (30-50 m tall) (%)	26-31	44-55	66-77
Model trees with break (30-50 m tall)	0-1 ²	1	2
Pieces per tree	2	3	5
Proportion of tree height to first break	0.75	0.5	0.25
Location of breaks beyond the first ³	--	0.5	0.5

¹per 10-m riparian section per century for each 5-m height class (e.g., three 15-m tall trees fall from 0-10 m upslope per century).

²We chose not to break trees in the 30, 35 and 40 m height class to emphasize minimum effects of breakage.

³Location relative to the length of the piece to be broken.

Ninety trees capable of spanning the channel entered the stream per century (45 from each bank) (Table 13). Of these, 80 pieces of wood spanning the channel entered the stream per century under the no breakage scenario. In the average fall breakage scenario, 36 trees broke at least once on impact (20 for minimum effect and 72 for maximum effect). In the stream channel only, the average breakage produced 129% of the total number of pieces compared to no breakage (Table 13 and Fig. 15). The low breakage

scenario produced 108% and the high breakage scenario produced 180% (Table 13 and Fig. 15).

The most interesting aspect of these model scenarios was the effect on pieces spanning the channel. Pieces that span channels have the greatest stability in streams and are most likely to form jams and pools (Bilby and Ward 1989; Martin and Benda 2001). In average and low breakage scenarios, 80 and 93% of channel-spanning wood pieces were produced, respectively, in comparison with the no breakage scenario (Table 13). In the high breakage scenario, only 21% of the channel-spanning pieces were produced (Table 13). Additionally, the source distance of channel-spanning pieces changed among the breakage scenarios. As breakage rates and pieces produced increased, source distance of channel-spanning wood peaked in the 10-20 m zone (Table 13 and Fig. 16).

Length frequency distributions of wood in the stream differed among breakage scenarios (Fig. 17). Under the no breakage scenario, wood length distribution reflected the height of trees entering the stream. The low breakage scenario was similar to no breakage, with 2-4% of pieces in the smaller size classes. The average breakage scenario produced 3-22% more pieces in the smallest size classes and reduced the frequency of the largest length classes by approximately 60% (Fig. 17). The high breakage scenario produced the largest increase in the smallest size classes compared to no

breakage (Fig. 17). Also, high breakage eliminated the presence of the longest length classes (Fig. 17).

Table 13. Model results of effects of fall breakage on number of stream wood pieces entering a 10-m wide stream over a 200-m long reach. Tree fall was directly towards the channel. See Table 12 for model parameters.

Model result	No breakage	Low breakage	Average breakage	High breakage
Wood pieces entering stream ¹	90	96	116	162
0-10 m	38	40	46	62
10-20 m	32	34	44	56
20-30 m	20	22	26	44
Channel-spanning wood pieces entering stream	80	64	74	17
0-10 m	38	32	36	6
10-20 m	32	22	24	14
20-30 m	20	10	14	0
Wood pieces entering stream / no breakage (%)	100	108	129	180
Channel-spanning wood pieces entering stream / no breakage (%)	100	93	80	21

¹Includes all pieces in or partially in the active channel

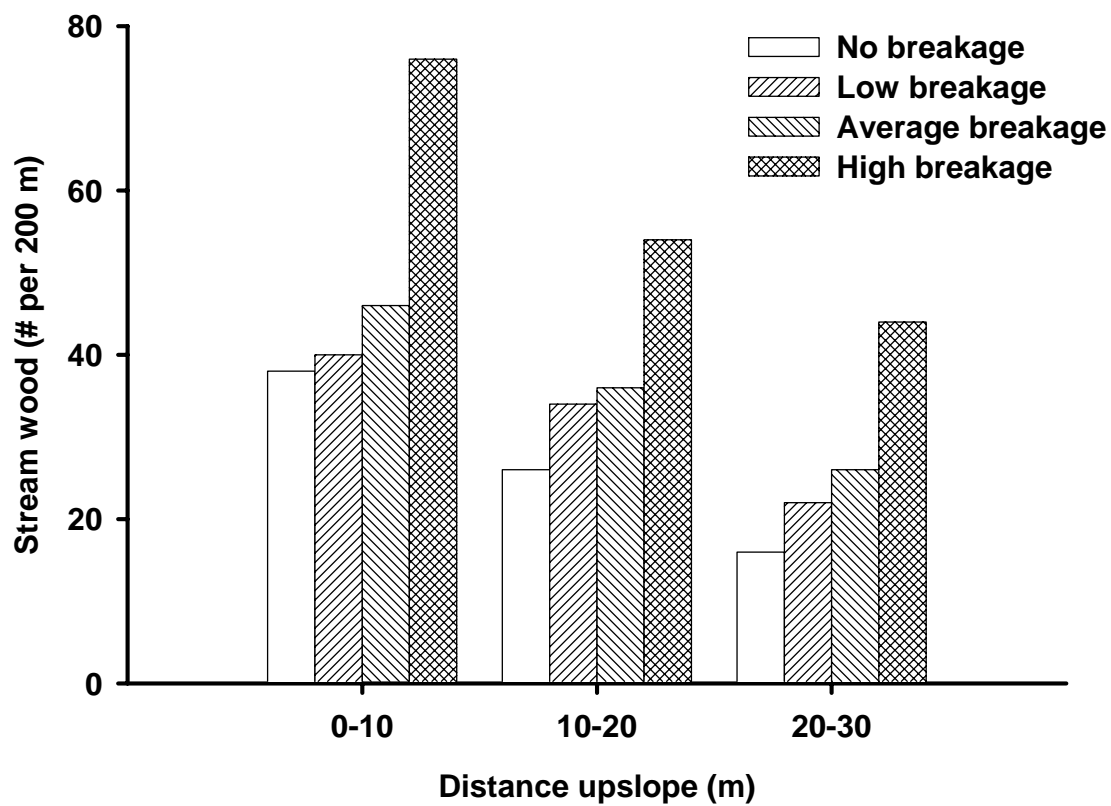


Fig. 15. Number of wood pieces entering a model 10-m wide stream over a 200-m reach per century in four scenarios of tree fall breakage (see Table 13 for specific parameters).

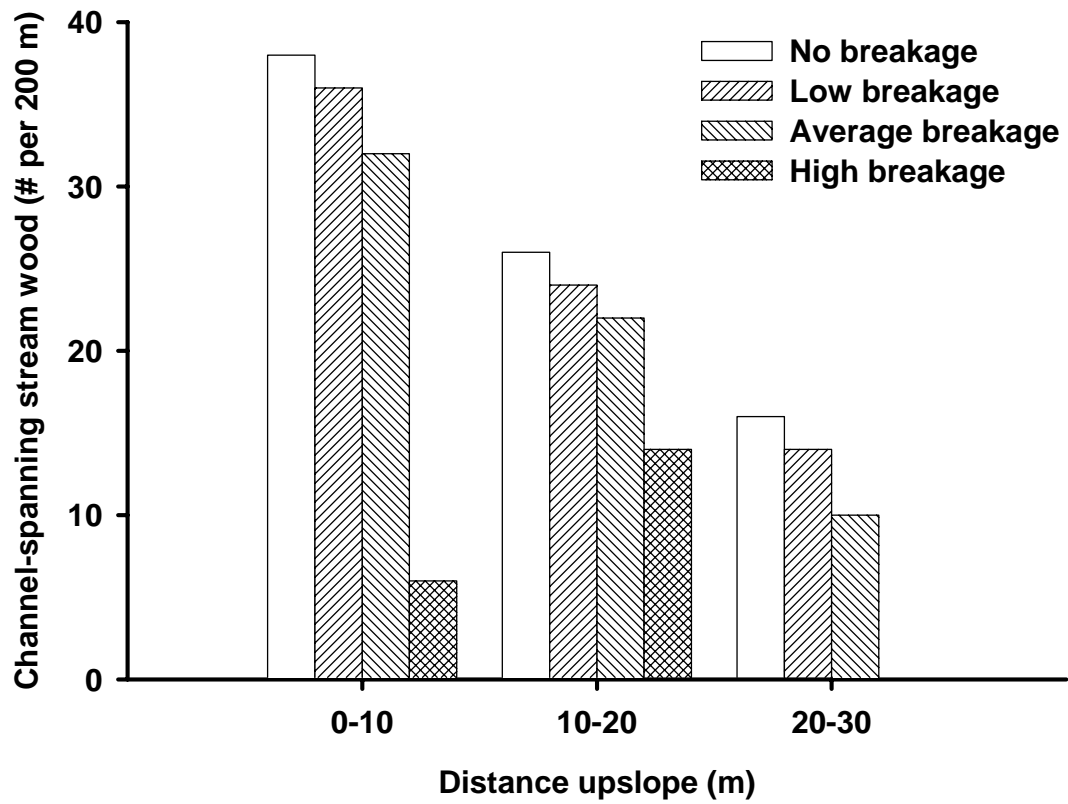


Fig. 16. Number of channel-spanning wood pieces entering a model 10-m wide stream in the Pacific Northwest per century in four scenarios of tree fall breakage (see Table 13 for specific parameters).

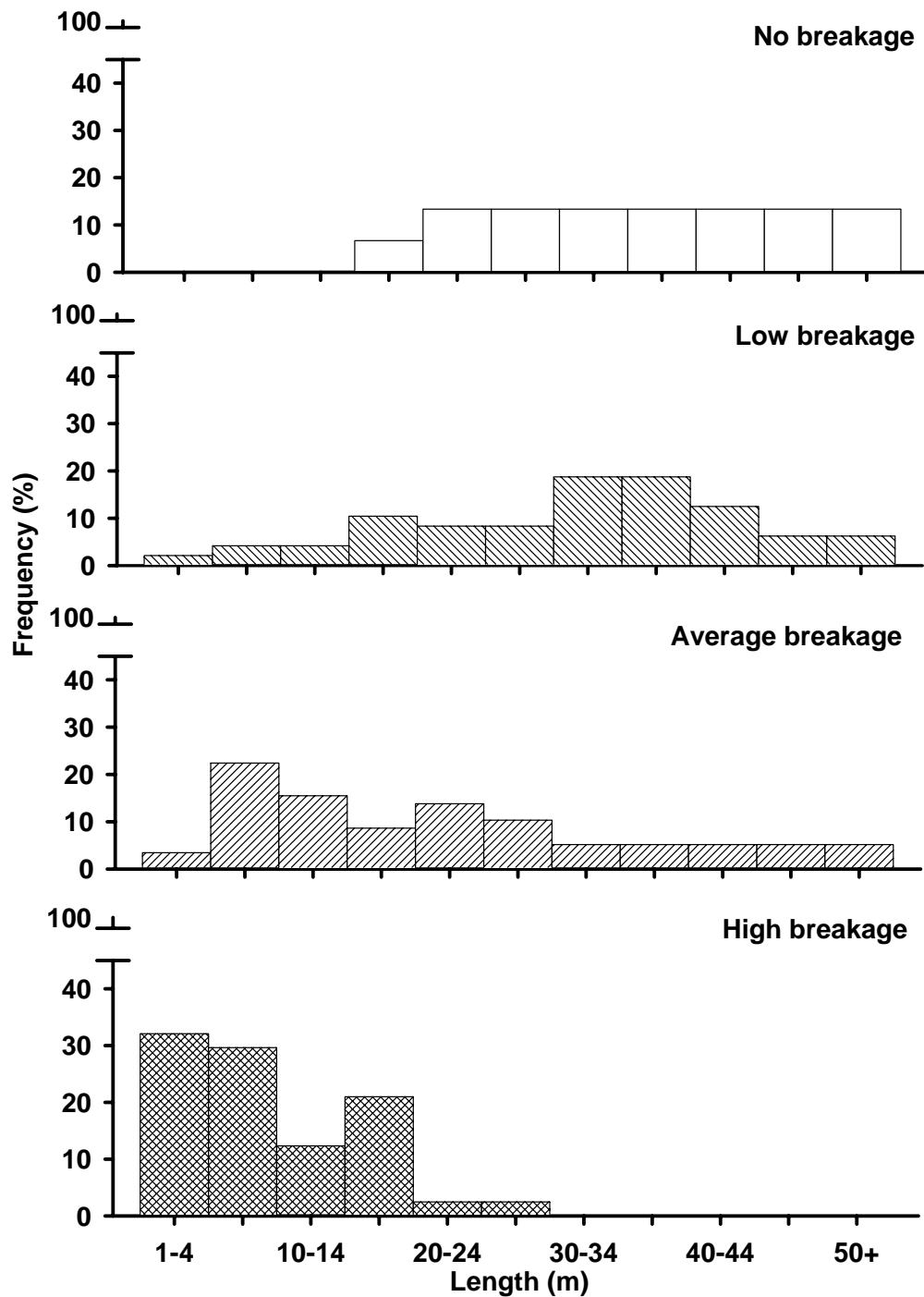


Fig. 17. Length frequency distribution of wood entering a model 10-m wide stream over a 200-m long reach per century in four scenarios of breakage by trees falling in the model stream (see Table 13 for specific parameters).

DISCUSSION

Land and resource managers are faced with many challenges in developing strategies for restoring and sustaining long-term presence of wood in streams (Oregon Department of Forestry 1994; Gregory 1997). Piece length is a major determinant of functional status and residence time in channels (Lienkaemper and Swanson 1987; Bilby and Ward 1989). Thus, identifying processes that control abundance and functional roles of wood in streams is critical for proper ecosystem management. This research provides valuable information on rates and patterns of fall breakage in streams and riparian areas. We also demonstrated that fall breakage may have a wide range of effects on abundance and length frequency distribution of wood entering streams.

Greater percentages of breakage during felling operations have been observed in areas with numerous rock outcrops, standing stumps or down timber in comparison to level, spongy ground surfaces (Rapraeger 1932). We did not detect trends in fall breakage according to physical characteristics of stream valleys in this study. Most breaks were not attributable to physical features among study sites. We did not experimentally manipulate directions of tree fall to maximize influence of slope or ground obstacles on breakage, as was done in previous felling studies. Further, this survey did not explicitly select trees that were merchantable wood. Variation in wood structural

integrity and decay status may have obscured effects of physical features on the fall breakage process. Specific gravity of wood ($\text{g}\cdot\text{mL}^{-1}$) is a universal measure of wood structural integrity and differs among species (Haygreen and Bowyer 1996). But, this measure (and structural integrity) also is extremely sensitive to wood moisture content, decay status and life history of the tree (Rapraeger 1932; Haygreen and Bowyer 1996). Additionally, areas of insect infestation, fungal infection or other areas of diminished strength (knots) on tree boles require less force to break compared to structurally unaltered wood (Huber 1918, Rapraeger 1932; Sumiya 1963). In an analogy, 90% of observed mechanical failures in giant kelp (*Nereocystis luekeana*) from Friday Harbor, WA, occurred where sea urchin bites or wave abrasion had caused flaws (Koehl and Wainright 1977). Analogous mechanisms that cause structural flaws in standing trees—such as insect infestation and impact from other falling trees—probably affect rates and patterns of fall breakage. Our study did not make strong inference to effects of wood structural integrity because exact condition (live, dead or internally rotten) and decay state of trees at the time of fall was unknown. The mode of tree fall (root-thrown versus stem-broken) was probably a weak indicator of wood structure at time of fall. Additionally, differences of breakage rates and patterns were slight among species except for western larch. At sites where western larch was found, we noted that standing specimens of the species typically were dead. Therefore, breakage rates and patterns for this species may reflect breakage

of snags of this species hitting stream and riparian surfaces. Overall, we suggest that individual tree-based differences in wood structural integrity produced high variation in fall breakage rates and patterns in riparian trees at study sites.

Surprisingly, slope steepness and upslope distance from the channel were not associated with rates or patterns of fall breakage. In a study examining effects of tree size and topography on merchantable timber losses from breakage in the Pacific Northwest, percentage of breakage in Douglas fir increased from ~8% on slopes 0-20% to 14% on slopes > 40%, respectively (Rapraeger 1932). Other species (western hemlock and grand fir) showed similar breakage responses. In a study of 39 stream reaches in western Oregon and Washington, shorter overall piece lengths (median of 15.0 m) in steep-sided valley segments with numerous in-stream boulders and cobbles in comparison to wood in broad valley alluvial segments (median length of 20.7 m) were attributed to high rates of fall breakage in the constrained segments (McDade et al. 1990). In this study, we did not find that probability of fall breakage was greater on steeper slopes or farther away from the stream channel. Again, variability of wood structural integrity may cause significant amounts of fall breakage and thus reduce ability to detect effects of side slope or proximity to the stream.

On interesting note, we did not detect a strong difference in fall breakage patterns between red alder and conifer species (Fig. 7).

Observations from the Olympic Peninsula, WA, suggest that red alder experiences higher breakage rates (cumulative of fall and in-channel processes) compared to softwood species (McHenry et al. 1998). Though hardwood structure is typically much more complex (diverse cell types and interlocking fibers) compared to softwoods (90-95% longitudinal tracheid cells and straight-grained) (Haygreen and Bowyer 1996), alder species actually have wood structure more typical of softwood species (Harlow and Harrar 1968). Decomposition rates of red alder are much faster than conifer species because of low carbon-to-nitrogen (C:N) ratios (~20:1) in wood compared with conifers (~200:1) (Baker et al. 1983). The stronger right tail skew in the length distribution of red alder wood compared to softwoods may partially result from in-channel fragmentation induced by accelerated decomposition rates after entering the channel rather than from fall impact.

Several studies examining felling techniques recommend that operators consider tree size when predicting timber that will be lost to breakage (Rapraeger 1932; Snell and Brown 1980). Based on a compilation of harvest data from the Pacific Northwest, 15% of merchantable bole volume was lost from felling breakage during harvest of old-growth Douglas-fir forests while trees from second-growth stands only lost 5% (Snell and Brown 1980). Previous studies of wood structural mechanics empirically demonstrate that resistance to breakage is inversely related to diameter (Sumiya 1963; Haygreen and Bowyer 1996). These studies evaluate representative wood

specimens while trees measured in this study probably had significant structural flaws, had irregular shapes, and were partially decomposed at time of fall. In this study, dbh was not a significant influence on probability of breakage. This may have effectively reduced capacity to detect influence of diameter on rates and patterns of fall breakage or, more importantly, our study may have captured the natural behavior of wood in riparian trees. Tree height was the only consistent variable that predicted probability of breakage and number of pieces produced. Integrating our results with timber harvest studies indicates that importance of fall breakage in determining piece lengths of wood entering channels increases as age of riparian stands increases (i.e., as trees grow taller).

Patterns of fall breakage were highly variable. Though we did not find strong shifts in breakage patterns by tree characteristics and rooting position, central tendencies and variation were quantified. For trees that broke, two to three pieces usually were produced regardless of site conditions. Additionally, first break occurred at approximately half tree height, though SD was ± 0.24 proportional units relative to tree height. Several previous studies also have found that trees break at points 50-75% of total tree height (Hunt and Henley 1981; Murphy 1984). As for our interpretation of break locations beyond the first, we only can suggest the locations were randomly distributed on the remaining pieces.

We empirically demonstrated that fall breakage rates and patterns have a wide range of impacts on number and length frequency distribution of wood entering channels. Though our model scenarios were deterministic, we selected our breakage rates and patterns based on variability observed in our field study. Undoubtedly, other random variation exists in breakage, stand mortality and spatial distribution of trees. Still, our model scenarios are innovative compared to previous modeling efforts because we incorporate real fall breakage data. Piece numbers were approximately 1.1 to 1.8 times greater under the three simple scenarios that included fall breakage compared to a no breakage model. Consequently, the length frequency distribution curve shifted from a uniform distribution in the no breakage scenario to dominance by shorter piece length classes in the high breakage scenario. Models that do not represent fall breakage produce inaccurate predictions of piece numbers and length frequency distributions (Van Sickle and Gregory 1990). A sensitivity analysis of a stream wood dynamics model for fifth-order and smaller stream basins demonstrated that pieces longer than 20 m increased by ~15% when a fall breakage function was excluded (500 years in a Douglas-fir forest) (Meleason 2001).

The most interesting aspect of our fall breakage modeling was the effect on recruitment of wood pieces that spanned the channel. In the low breakage scenario, 93% of channel-spanning pieces were produced compared to no breakage. Only 21% were produced in the high breakage

scenario. These results have important implications for predicting functional roles of wood in streams over time. Channel-spanning pieces are typically the most stable wood pieces in channels (Bilby 1984; Lienkaemper and Swanson 1987; Young 1994). Empirical relationships between length, diameter and size relative to the channel have been developed to predict pool forming and sediment storing capabilities of wood in streams (Bilby and Ward 1989; Beechie et al. 2000). Processes regulating dynamics of pool- and jam-forming wood pieces are poorly understood. Based on our results, fall breakage can strongly affect recruitment of extremely large pieces of wood. Results also suggest wood that does not span the channel also may be highly stable because of large portions of pieces remain anchored to the bank.

In forested regions of the Pacific Northwest, processes that control amount and size distribution of wood in channels directly affect stream ecosystem structure and function (Harmon et al. 1986; Lienkaemper and Swanson 1987; Bilby and Ward 1989; Meleason 2001). Fall breakage is one of several processes that influence size distribution of wood in streams. We have provided evidence that fall breakage can effectively reduce frequency of extremely large pieces of wood entering stream channels. An individual-based model of stream wood dynamics has demonstrated that in-channel breakage significantly elevates frequency of pieces in the shortest length classes (Meleason 2001). Physical fragmentation and biological decomposition also influence wood size in channels (Ward and Aumen 1986;

Murphy and Koski 1989). Long-term effects of each of these processes, including fall breakage, on piece size distribution and wood dynamics is poorly understood. Our major contribution to knowledge of dynamics of wood in streams is empirical data on a fundamental process of wood recruitment from riparian forests. This information allows wood dynamics to be modeled more accurately in evaluations of future conditions of alternatively managed forested landscapes.

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CONCLUSIONS

Information on fall directions and breakage of riparian trees in this thesis allows land and resource managers to predict delivery of wood based on riparian forest dynamics and evaluate long-term implications of alternative landscapes more accurately. Though random selection of streams was not possible (study sites were selected randomly), I observed several trends in fall directions and breakage patterns across study sites. Empirical relationships on processes of wood recruitment defined in Chapters 2 and 3 should add greater accuracy to management for stream wood and riparian forest dynamics. Specifically, the most important empirical models that can be directly incorporated into wood recruitment models are effects of side slope steepness and rooting position on riparian tree fall direction and effects of tree height (with or without differences based on species) on probability of fall breakage.

The important findings from the riparian tree fall component of this research (Chapter 2) were that tree fall was directional and fall directionality changed with several topographic and geomorphic features of the stream valley. Though trees generally fell towards the channel regardless tree characteristic or environmental variable, variance of tree fall directions was greater on gentle side slopes versus steep side slopes and on valley bottoms versus hillslopes landforms. Several sites that had relatively high tree height/dbh ratios exhibited general upstream fall directions. Based on a probabilistic model of tree fall into streams (McDade et al. 1990; Van

Sickle and Gregory 1990), this change in fall directionality may reduce wood recruitment from riparian forests by as much as 50% compared to sites with tree fall towards the channel and effectively shrink wood source distance adjacent to streams (Appendix B).

Several important questions emerged from the fall direction component. The central tendency for trees to fall towards streams and changes in fall variance according to rooting position indicate that several growth patterns (i.e., tree lean and phototropic responses) by individual trees influence the probability of eventual fall direction. Long-term monitoring of riparian forests and modeling efforts may provide stronger empirical evidence for this effect. A physical model of tree fall direction as a function of tree lean and wind direction has been constructed, but model validation indicated predictive capability was weak (Bustos-Letelier 1994). General upstream tree fall at three sites with high tree height/dbh ratios may reflect an interaction between stand dynamics and winds funneling up the stream valley. More extensive surveys are needed to analyze this pattern because only three sites exhibited the relationship.

In the fall breakage component (Chapter 3), I found that rates and patterns of fall breakage were highly variable. Tree height was most strongly correlated with probability of breakage. Influence of species type was minor and may be explained by the condition of the tree species at time of fall (western larch had greater rates of breakage; standing

specimens typically were dead at study sites). I also found that trees experienced slightly greater percentages of breakage in older riparian stands. Trees that broke typically produced 2 to 3 pieces and the location of first break occurred at approximately half tree height (SD of ± 0.24 height proportion units). The majority of fall breaks (~62%) could not be attributed to physical factors of the stream channel or riparian area. Height was the statistically strongest factor related to number pieces produced from fall breakage, but the exact relationship was difficult to determine because of high variance. Location of first break on tree boles was not strongly associated with any measured parameter; breaks beyond the first occurred at random locations.

The fall breakage component also identified several questions for future research. Except western larch, I did not detect differences in breakage rates among species, though previous work in the wood products industry clearly indicates differences (Rapraeger 1932; Haygreen and Bowyer 1996). However, this study fundamentally differed because I examined natural fall breakage whereas those from the wood products industry specifically considered merchantable timber lost during felling operations (Rapraeger 1932; Snell and Brown 1980; Hunt and Henley 1981). Two mechanisms may be responsible for the highly variable rates and patterns of fall breakage quantified in this study. (1) High variability in fall breakage patterns and lack of numerous significant differences among

species may have resulted from individual-tree based differences in wood structural integrity at time of fall. (2) Riparian trees fall into complex microtopographic conditions (e.g., down wood, boulders/rock outcrops, coarse stream substrates and abandoned stream channels). As a consequence of the observational design and coarse-scale of this study, I could not explicitly assess properties of wood strength and decay status at time of fall or minute details of topographic conditions for each individual tree. Long-term monitoring or field experimentation may be needed to gain insight on the influence of tree-specific wood structural integrity on the fall breakage process in streams and riparian zones. Identifying effects of structural integrity on breakage rates and patterns by falling riparian trees could permit more accurate assessments of potential channel-spanning (pool- or jam-forming) wood pieces entering a stream channel.

Models of tree fall directionality and fall breakage constructed in this research are most applicable to streams that receive a majority of wood from endogenous riparian forest dynamics. Management implications based on this study may not apply to streams and rivers that actively recruit a majority of their stream wood through bank erosion, floods and other fluvial processes. Also, this thesis does not quantify recruitment associated with debris flows, fires or other catastrophic events that can temporarily double or triple standing stocks of wood volume in individual streams or reaches (Benda and Sias 1998).

Models that simulate multiple long-term ecosystem functions of riparian zones along small- to mid-sized streams should incorporate riparian tree fall directionality and breakage in evaluation of long-term and large-scale dynamics of forest management regimes across the Pacific Northwest. These data are important to accurately predict delivery of wood to streams, which is a critical component of ecosystem function in forested regions of the Pacific Northwest (Bilby and Bisson 1999). Studies that describe important landscape-level processes such as wood delivery to streams are essential because a cornerstone objective of ecosystem management is to maintain ecological and evolutionary processes across landscapes (Grumbine 1994).

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APPENDICES

APPENDIX A. CIRCULAR STATISTICAL TECHNIQUES

A problem arises when calculating summary statistics for angular data because traditional linear methods fail to properly represent the average of a sample from a population of angles (Fisher 1993). For example, the average of 350° and 10° is 0° ; not 180° as would be calculated by traditional linear statistics. The average angle, \bar{q} , can be determined by adding, heading to tail, unit vectors with angle q_i . The resultant vector has angle \bar{q} . Mathematically, \bar{q} can be computed from:

$$[A1] \quad C = \sum_{i=1}^n \cos q_i$$

$$[A2] \quad S = \sum_{i=1}^n \sin q_i$$

$$[A3] \quad R^2 = C^2 + S^2$$

Then,

$$[A5] \quad \bar{q} = \cos^{-1}(C/R)$$

or

$$[A6] \quad \bar{q} = \sin^{-1}(S/R)$$

Circular variance (V) and standard deviation (CSD) are calculated by the following procedure:

$$[A7] \quad \bar{R} = R/n$$

$$[A8] \quad V = 1 - \bar{R}$$

$$[A9] \quad \text{CSD} = \{-2\log(1-V)\}^{1/2}$$

This calculation of variance is most useful for groups of angles that comprise a single group (i.e., unimodal distribution) because $V = 1$ does not necessarily imply complete dispersion. CSD has units of radians. See Fisher (1993) for more discussion.

APPENDIX B. UPSTREAM VERSUS TOWARDS CHANNEL FALL

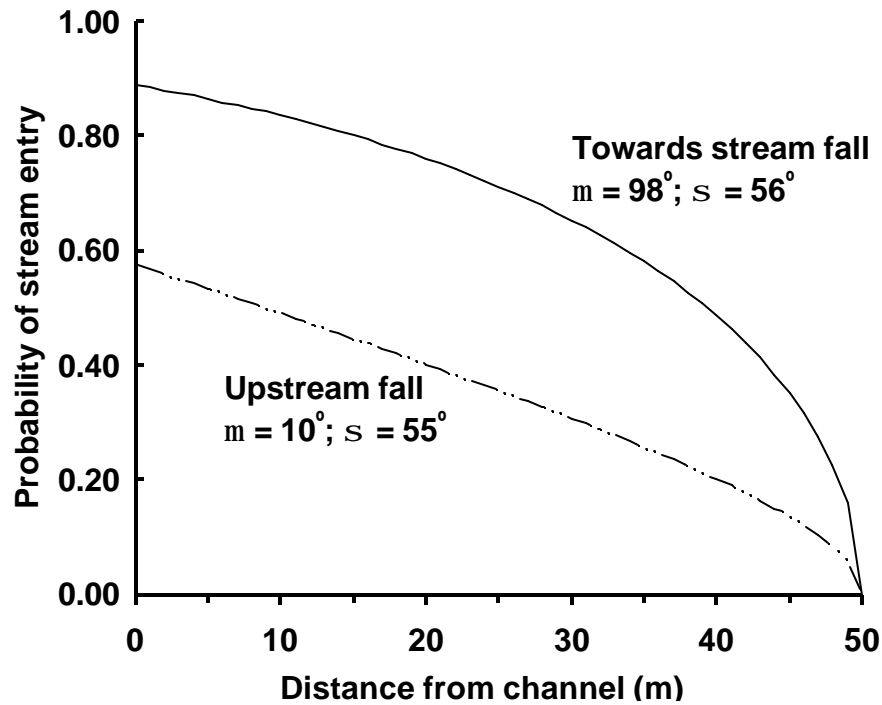


Fig. B1. Probability of riparian tree fall into a stream for the 50-m height class as a function of distance from the channel. Parameters for upstream fall are based on averages of mean fall direction and circular standard deviation for three sites and towards channel fall is based on averages of statistics from 16 sites with this general fall pattern. See eq. 3 in Chapter 2 for details.