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Modeling Large Woody Debris Recruitment for Small Streams of the Central Rocky Mountains

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Abstract

As our understanding of the importance of large woody debris (LWD) evolves, planning for its production in riparian forest management is becoming more widely recognized. This report details the development of a model (CWD, version 1.4) that predicts LWD inputs, including descriptions of the field sampling used to parameterize parts of the model, the theoretical and practical underpinnings of the model's structure, and a case study of CWD's application to a stream in Wyoming's Bridger-Teton National Forest.

Keywords: riparian, FVS, CWD, spruce-fir, old-growth, dead wood, disturbance, management

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Cover photo: *Beginning its journey as riparian large woody debris, this recently toppled blue spruce in the upper Greys River drainage of the Bridger-Teton National Forest in Wyoming will contribute much to the structure and function of this stream.*

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Contents

Introduction

After decades of neglect and abuse, riparian zones are now recognized as critical components of aquatic and terrestrial ecosystems (Johnson et al. 1995, Sparks 1995). Streams link seemingly disparate communities with flows of energy, nutrients, biomass, and water (Swanson et al. 1982, Gregory et al. 1991, Chen et al. 1995); sustain movement corridors (Knight 1994, Sparks 1995); provide localized increases in diversity, both biotic and structural (Swanson et al. 1982, Gregory et al. 1991, Knight 1994, Sparks 1995); and support numerous human activities (Budd et al. 1987, Meehan 1991, Knight 1994). Despite the importance of these dynamic systems, little has been done to ensure their retention of structural, biotic, and functional integrity when the surrounding forests are intensively managed. Most riparian zone management strategies rely on fixed buffers to protect critical processes. However, buffers often fail to include important sources of biomass or nutrients or they may include too expansive an area, thereby including parts of the landscape better suited for more intensive management (Bren 1995). Recent reviews of the impacts of riparian buffer zones (Steinblums et al. 1984, Budd et al. 1987, Ralph et al. 1994) have quantified the ecological differences between managed and unmanaged watersheds, indicating the need for more attention to riparian management area (RMA) design and implementation.

To address both ecological and socioeconomic concerns, the RMA must preserve ecosystem function rather than focusing on administrative expedience. Factors that determine the effectiveness of riparian forests include the regulation of thermal and solar regimes, sedimentation rate, habitat quality, and large woody debris (LWD) production (Swanson et al. 1982, Steinblums et al. 1984, Budd et al. 1987, Gregory et al. 1991). Monitoring and maintaining LWD (we define LWD as any structurally sound piece of wood ≥1 m in length and ≥10 cm diameter) is important because of its influence on channel development (Triska and Cromack 1980, Bisson et al. 1987, Ralph et al. 1994, Ruediger and Ward 1996), sediment trapping and storage (Beschta 1979, Likens and Bilby 1982, Megahan 1982, Bilby 1984, Bilby and Ward 1989, Potts and Anderson 1990), oxygenation and turbulent mixing of water (Bisson et al. 1987, Sedell et al. 1988), organic carbon and nutrient cycling (Bilby and Likens 1980, Swanson et al. 1982, Harmon et al. 1986, Gregory et al. 1991), and species habitat (Maser and Trappe 1984, Harmon et al. 1986, House and Boehne 1987). Riparian LWD characteristics vary, depending on the condition and distribution of the pieces, stream width and volume, disturbance regime, and the degree of human intervention (Swanson et al. 1982, House and Boehne 1987, Bilby and Ward 1989, Ralph et al. 1994, Berg 1995, Bragg 1997).

Anticipating changes to riparian LWD pattern and process provides managers with the ability to assess the impacts of forest management practices on this resource, predict long-term riparian debris dynamics, and assist in the recovery of channels altered by severe changes. Although models to predict LWD delivery for some regions are available (Swanson et al. 1976, Rainville et al. 1985, Budd et al. 1987, Lienkaemper and Swanson 1987, Bilby and Ward 1989, McDade et al. 1990, Van Sickle and Gregory 1990, Ralph et al. 1994), the next step is to develop usable management tools and strategies. A holistic approach would integrate the components that determine riparian system behavior and readily provide information on which resource managers can base decisions. This involves incorporation of existing technology, including predictive management models. In this paper, we present a riparian LWD recruitment model (CWD, version 1.4), to predict LWD delivery to small riparian systems of the central Rocky Mountains as a tool to assist in riparian zone management.

Study Area Description

Regional Physiography and Climate

Data to assist in model development were collected on the Bridger-Teton National Forest (BTNF) during the summer of 1995. Located in the northwestern corner of Wyoming, the BTNF extends from the southern boundary of Yellowstone and Grand Teton National Parks down the spines of the Wind River, Gros Ventre, Absaroka, Hoback, Wyoming, and Salt River Mountains. Elevations range from 2000 to > 4000 m, with most of the BTNF exceeding 2100 m. Annual precipitation (primarily as snow) varies from 35 to 150 cm, and the growing season tends to be short (< 100 d).

Geologically, the BTNF encompasses a diverse mixture of landforms and processes. Many of the sedimentary mountains arose from low-angle faulting, producing a geological province known as the Overthrust Belt (Lageson and Spearing 1988, Knight 1994). The Wind River Mountains are of granitic rather than sedimentary origin, and some areas (especially the Absaroka Mountains) resulted from volcanic activity. During the Quaternary Period, ice shaped the surface of the BTNF as most ranges experienced extensive glaciation (Knight 1994). Erosion, landslides, vulcanism, tectonics, biota, and human activity have further shaped the face of the region in the intervening millennia (Love and Love 1980, Lageson and Spearing 1988, Knight 1994).

Stream Systems

The BTNF drains into 3 primary watersheds: the Snake, Green, and Bear. The highly dissected landscape and heavy winter snows sustain many streams, ranging from small snow-melt ephemerals to large permanent flows like the Snake, Buffalo Fork, Hoback, Green, and Gros Ventre Rivers. We selected individual streams for consistent, old-growth spruce-fir cover, low levels of human disturbance, accessibility, and relatively small channels. Most of our sample streams were moderate in gradient (2% to 10%), with sinuosities on sampled reaches ≤ 1.5 (table 1). Low sinuosity streams were chosen to minimize channel braiding, meandered cutoffs, and other difficult-to-model stream patterns.

Vegetation

Watersheds with a high proportion of forest were selected, but some areas along major drainages included grassland or rock (especially along major drainages). Vegetation cover is frequently patchy in the central Rocky Mountains, with sagebrush/grassland occurring on exposed southern and western aspects. Forests typically occupy northern and eastern slopes, higher elevations, and sheltered bottomlands and bowls, often interspersed with steep rocky slopes, cliff faces, and summits. Timberlands on the BTNF are primarily coniferous, dominated by lodgepole pine (*Pinus contorta* Dougl. ex Loud.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). Minor components of blue spruce (*Picea pungens* Engelm.), limber pine (*Pinus flexilis* James), whitebark

Table 1. Characteristics of stream reaches in northwestern Wyoming.

Stream	Order	Upstream basin size (ha)	Mean elevation (m)	Mean bankfull width (m)	Reach gradient (%)	Reach sinuosity
Adams Creek	1	1098	2067	3.0	6.9	1.13
Moose Gulch Creek	1	417	2152	3.4	2.0	1.12
Murphy Creek	1	858	2061	6.1	2.9	1.15
Blind Bull Creek	2	2318	2122	5.7	4.9	1.17
Buck Creek	2	1326	1897	4.8	8.5	1.09
Dry Lake Creek	2	1033	2565	5.5	3.5	1.05[a]
South Fork Gypsum Creek	2	2309	2395	12.0	10.0	1.02[a]
Sheep Creek	2	1958	2450	4.6	6.7	1.06
Willow Creek	2	1774	2407	4.6	4.8	1.10
Blackrock Creek	3	9078	2498	17.6	5.0	1.07[a]
Ditch Creek	3	4450	2240	11.2	2.2	1.20
Hoback River	3	9965	2271	14.4	1.5	1.02[a]
Mosquito Creek	3	2512	2119	9.2	2.0	1.23

[a] *Estimated from 1:24,000 topographic maps.*

pine (*Pinus albicaulis* Engelm.), and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) are also present. Clonal trembling aspen (*Populus tremuloides* Michx.) is found in sheltered sites, while some larger streams are lined with groves of cottonwoods (primarily *Populus angustifolium* James and *Populus trichocarpa* Torr. & Gray). Spruce-fir-dominated unmanaged old-growth riparian forests, including transitional stands of lodgepole pine and Douglas-fir, were of primary interest in the development of CWD, but the model can simulate other types.

Methods

Field Sampling

To provide an adequate estimate of in-stream LWD loading (Nakamura and Swanson 1994), we established 13 plots (figure 1) along 300 m reaches flowing through relatively continuous, spruce-fir-

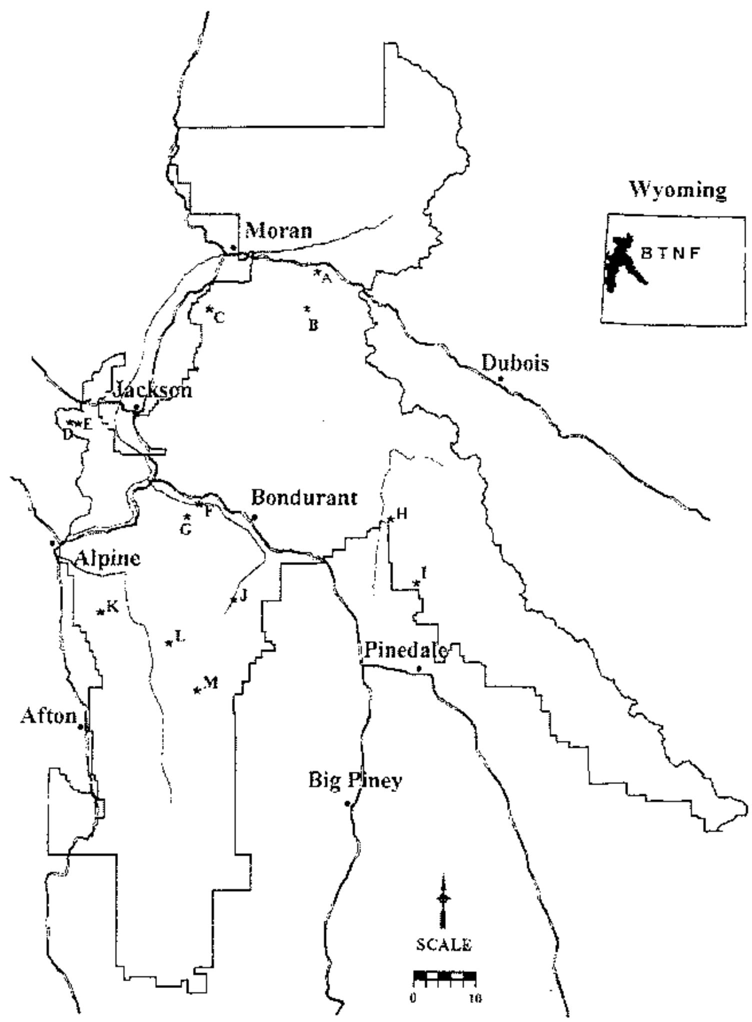

Figure 1. Large woody debris study plot locations established on the Bridger-Teton National Forest (BTNF) during the summer of 1995. A— Blackrock Creek; B— Dry Lake Creek, used for the simulations in this paper; C— Ditch Creek; D— Moose Gulch Creek; E— Mosquito Creek; F— Buck Creek; G— Adams Creek; H— South Fork Gypsum Creek; I— Willow Creek; J— Hoback River; K— Murphy Creek; L— Blind Bull Creek; and M— Sheep Creek.

dominated old-growth. Measurements of stream and riparian forest characteristics of LWD conditions yielded a comparison with other regions and described important riparian LWD patterns (e.g., angle of stem fall, snag fragmentation). In field sampling, we focused on stand characterization, volume of riparian forest LWD, stream characterization, and stream LWD volume. Most LWD inventory variables are in terms of volume (m^3) because this was easily calculated from field data.

Stand Characterization

Six 0.1 ha circular subplots centered 20 m from the bankfull edge were established along two-250 m transects parallel to each bank. We recorded the following for all living stems ≥ 10 cm diameter at breast height (DBH): species, height (m), diameter (cm), and angle of lean (in degrees) relative to the stream recorded. From these measurements, individual tree volume (m^3), stand volume (m^3/ha), stand density (m^2/ha), and species composition (%) were estimated. Habitat type (Steele et al. 1983) was also determined for each subplot.

Riparian Forest LWD

In addition to living biomass measurements, data were taken on riparian forest LWD. Only pieces or portions of pieces within the plot radius were measured. When possible, LWD species was identified. We measured the end diameters and length for all pieces of debris and estimated its angle relative to the channel (figure 2). Mean piece volume (m^3), LWD volume (m^3/ha), and number of pieces (per ha) were derived from this data.

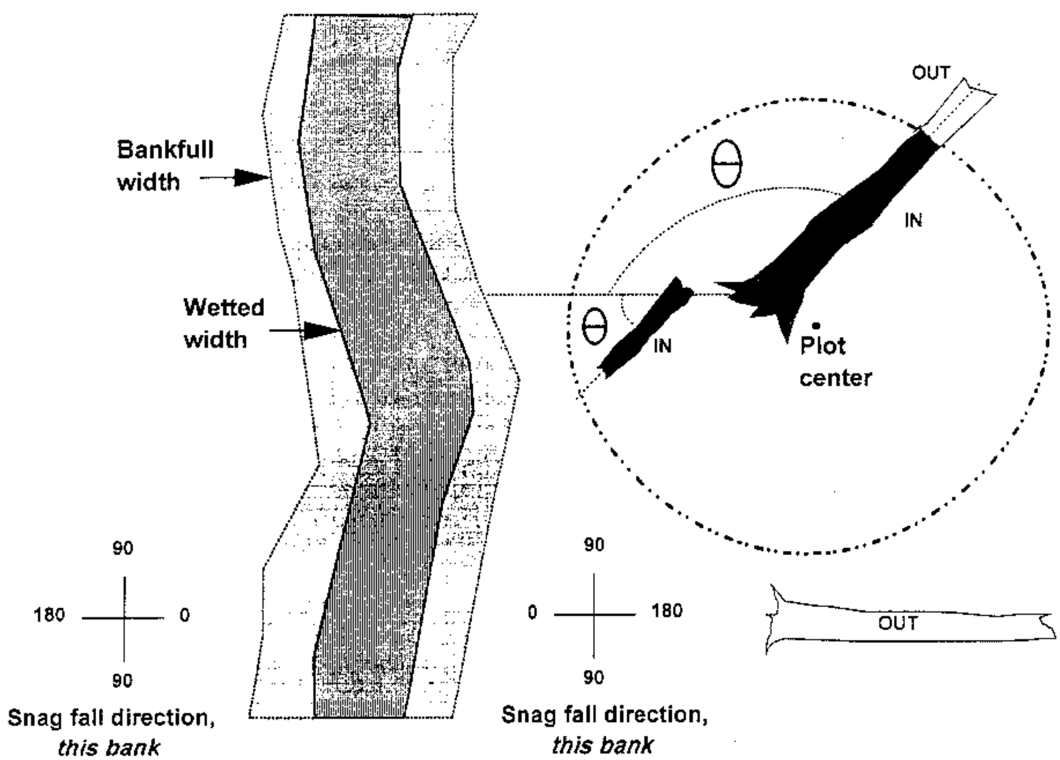

Figure 2. Diagrammatic view of field sampling procedures. Plot center for each 0.1 ha subplot was located 20 m from the stream. Each piece of riparian forest large woody debris (LWD) that fell entirely within plot radius was tallied. Long pieces that extended outside of the plot radius were measured to the edge of the subplot, but not beyond, ensuring accurate per ha estimates of LWD volume. Each "in" piece also had its angle relative to the stream (0° ≤ θ ≤180°) estimated.

Stream Characterization

Streams were characterized by order (Strahler 1957), basin size (ha), reach midpoint elevation (m), mean bankfull width (m), reach gradient (%), and sinuosity. Reach midpoint elevation, gradient, and some sinuosities (table 1) were taken from 1:24,000 topographic quad sheets, while mean bankfull width and the remaining sinuosities were measured in the field.

Riparian LWD

Since we were interested in the debris that affected stream processes, and because channels can shift rapidly or pieces could be forcefully moved by the stream, we defined riparian LWD differently from forest LWD. Any LWD that extended 1 m or more over bankfull width was tallied and the entire length (to a 10 cm diameter) was included (figure 3). Although this delineation has been used by some (e.g., Richmond and Fausch 1995), others define riparian LWD differently (Lienkaemper and Swanson 1987, Carlson et al. 1990, Robison and Beschta 1990a, Ralph et al. 1994). The lack of standardization makes it difficult to cross-reference stream LWD loads between studies. However, we felt our approach to riparian LWD best addressed the uncertain nature of dynamic stream systems because it allowed us to tally of the most influential pieces.

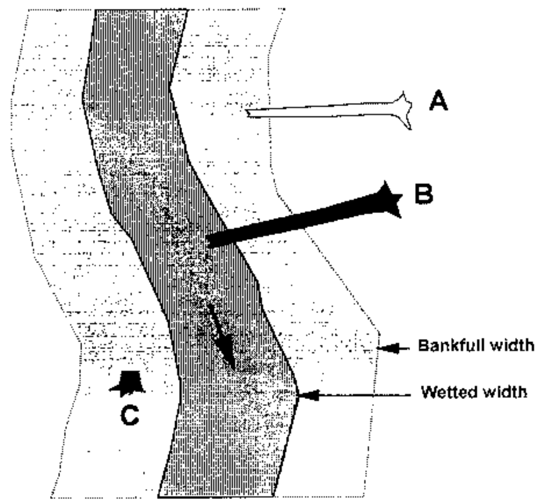

Figure 3. A different approach was taken to determine riparian large woody debris (LWD) because of uncertainties related to bankfull width and piece stability through time. Any piece (A) that did not enter the bankfull width by more than 1 m or did not extend more than 1 m over bankfull width with a minimum diameter of 10 cm was not considered riparian LWD. However, once the piece met this criteria (B and C), then the entire length of the piece was tallied. Any stump or rootwad (C) with > 0.25 m^3 estimated volume within the bankfull zone was also counted as riparian LWD.

Application of the Forest Vegetation Simulator (FVS)

The Forest Vegetation Simulator (FVS, also known as Prognosis (Wykoff et al. 1982)) is a growth and yield model that is used throughout the United States (Teck et al. 1996). FVS presented several definite advantages for our efforts. First, FVS is capable of simulating forest dynamics over extensive (up to 400 y) periods, allowing for long-term predictions of management effects. Second, FVS is flexible in the scheduling and application of timber harvests and regeneration, allowing the user to design harvest treatments for specific scenarios. Finally, FVS generates sufficiently detailed output (i.e., individual tree-based) to allow CWD to function. CWD was initially designed to operate with the Teton and Utah variants (version 6.1) of FVS. Reference Wykoff et al. (1982), Crookston (1990), Ferguson and Crookston (1991), Ferguson and Carlson (1993), and Teck et al. (1996) for information about FVS operation.

FVS simulated all modeled forest dynamics (e.g., regeneration, growth, mortality). FVS determines when to establish new trees, the growth of existing ones, and tree mortality based on user-defined defaults and internalized vegetation relationships. FVS was instructed by the key word file to generate a dead tree list, which provided attributes (current DBH, height, volume, crown condition, etc.) read by CWD. CWD acts as a post-processor on the output of FVS (Appendix A contains more detail on the interaction between FVS and CWD).

Generating Stand Dynamics with FVS

Modeling the behavior of woody debris in streams involved linking forest processes with stream dynamics. Trees become established, grow, die, and sooner or later fall over. Some pieces will eventually enter the channel and affect the pattern and process of that stream. While mortality rates, stem failure, and the interaction between them are random events, they can be estimated. For this project, we assumed that self-thinning yielded the most frequent mode of LWD production. FVS calculates mortality from quadratic mean diameter and stand basal area (density-dependent factors), which eventually becomes:

$$R_p = 1 - (1 - R_t)^p \qquad (1)$$

where R_p is the periodic survival rate and R_t is the estimated annual mortality rate (Wykoff et al. 1982). Additional mortality can be fixed within FVS by the user. Given a set of forest conditions, therefore, we can estimate the number of individual trees dying over a predetermined period. FVS apportions a number of stems into a mortality queue after every iteration. However, this only reveals the number of dead, standing snags, not the rate at which they fall over and become riparian LWD. To do this, one must determine the frequency of stem failure, which is a primary function of CWD.

CWD Model Development

Snag Spatial Location

After selection, each snag is randomly assigned a positional coordinate relative to the stream (not a Cartesian coordinate) to mark its distance from the stream. Stem location is important, as snags within 30 m of the channel have the greatest odds of stream entrance (Murphy and Koski 1989, McDade et al. 1990, Robison and Beschta 1990a, Van Sickle and Gregory 1990). With CWD, the user provides the breadth of the simulated riparian forest that controls snag proximity to the channel (see Appendix A). Unlike other regions (e.g., McDade et al. 1990), there seemed to be only minor upslope LWD contribution from debris flows or other log transport in the BTNF, so we assumed a riparian forest recruitment depth roughly equal to maximum potential tree height or about 35 to 40 m.

CWD defaults to random snag locations. Random spatial distributions have been noted for some forests (Ek 1969, Ishizuka 1984, Moeur 1993), but it is possible that riparian spruce-fir stands follow a different pattern. Therefore, CWD was designed to permit user flexibility in determining snag distribution (see Appendix A). Assigning the location relative to the channel also allowed us to avoid detailing stream position through time, so shifts in channel location do not effect the results. In CWD, users can include bank steepness to heslp determine if debris enters the bankfull channel by defining the elevation of the edge of the forest plot above the stream channel.

Snag Residency

Once a tree has been categorized as a snag, CWD determines how long it remains standing. In CWD, snag residency is a random process dependent upon species, diameter, and time since death, probably the most critical factors (e.g., Keen 1929, 1955; Mielke 1950, Hinds et al. 1965, Cline et al. 1980, Bull 1983, Cimon 1983, Raphael and Morrison 1987, Harrington 1996). However, there is little information about which factor is most important and about the timing of snag failure. In CWD, the user may adjust the weighting values for each component based on their particular needs (Appendix A). We subjectively biased these factors:

Time >> Diameter >> Species

Thus, we weighted time more heavily than diameter, which in turn was weighted more than species. Ample evidence suggests rapid snag fall within the first few decades after death, regardless of species or diameter (Keen 1929, 1955; Bull 1983, Schmid et al. 1985, Harrington 1996, Mitchell and Preisler 1998). A number of studies (Lyon 1977, Cline et al. 1980, Bull 1983, Cimon 1983, Raphael and Morrison 1987) found large-diameter trees fall at a slower rate than small-diameter stems. Bull (1983) and Raphael and Morrison (1987) have also compared snag failure rates between species and while some differences did exist, they were minor and perhaps more directly related to either diameter or cause of mortality (see also Hinds et al. 1965).

To calculate snag failure, each snag is processed through several steps. First, the snag is categorized by species to determine what inherent resistance it may have to failure. Since little information exists on the dynamics of stem breakage by species, we developed a formula using modulus of rupture (the maximum bending load to failure) data gathered from Panshin and deZeeuw (1980) for each species or a similar species. This allows for differences in the mechanical strength between species but does not account for unpredictable degradations (e.g., species-specific susceptibilities to heart rots, root rots, insect attack) that may weaken the stem.

After calculating the species modifier, we derived a diameter-based modifier. Although Curtis (1943) noted an exponential relationship between diameter and stem breakage caused by catastrophic winds, we cannot assume this because of other factors that also influence snag failure (e.g., wood decay, root rots, disturbance type). Again, sparse data were available for diameter-based snag failure; most studies consider decay rates only after the snag has fallen (e.g., Aho and Cahill 1984, Harmon et al. 1986, Harmon et al. 1987, Spies et al. 1988). We therefore simplified the relationship between stem failure and diameter to a negative linear trend that assigns the lowest vulnerability to large stems and the highest to small stems. This assumption probably best accounts for the leading factor in snag failure– wood decay. Mielke (1950) and Hinds et al. (1965) suggested that decay in the roots and lower portions of the bole was responsible for the majority of Engelmann spruce and lodgepole pine snag failures. Since the rate of wood decay is related to diameter, the larger the diameter of the tree, the longer it may persist as a snag. To determine the time of snag fall, where even partial loss of structural integrity may cause stem failure, we felt that a linear model of diameter-interaction was appropriate. The relationship between diameter and stem failure is also probably true for live trees broken by wind, snow, and other forces (Mergen 1954, Petty and Worrell 1981, Valinger and Fridman 1997).

To incorporate the effects of aging on snag residency, a time-based modifier was developed following a negative relationship between time and snag residency, a pattern supported by numerous studies (Keen 1929, 1955; Mielke 1950, Hinds et al. 1965, Schmid and Hinds 1974, Lyon 1977, Sollins 1982, Bull 1983, Schmid et al. 1985, Harrington 1996, Huggard 1997). Evidence indicates that snags rarely persist beyond 50 y (Schmid and Hinds 1974, Lyon 1977, Sollins 1982, Huggard 1997, Harrod et al. 1998), so a simple linear trend provided us with a conservative estimate of the relationship between time since death and snag residency. In CWD, snags that stand for more than one cycle are reduced in size to reflect their tendency to slowly fragment from the top down.

Finally, we included a harvest-based snag failure modifier to adjust for the impact of harvest on snag residency because as cutting intensity increases, snag density declines. Safety regulations require that most snags be felled at harvest time (e.g., Huggard 1997). This practice typically occurs when clearcutting, although ecosystem management protocols often call for the retention of some snags. Selective cuts and thins may preserve greater snag densities, but even then the impacts of felling and skidding logs may eliminate many snags. Harvest intensity can also be adapted to simulate the effects of a natural catastrophic disturbance on LWD recruitment (see Appendix A for other snag customization options).

Determining Angle of Snag Fall

The species, diameter, time, and harvest modifiers are summed for each snag and compared against a failure benchmark. If snag failure does not occur, the snag remains standing for another 10 y cycle and it is then reevaluated. If the snag falls, it is transferred into the LWD pool and an angle of fall is determined. Snags closer to the stream and falling towards it have a greater chance of influencing recruitment than a distant stem falling away from the channel (Van Sickle and Gregory 1990, McDade et al. 1990). Predicting this behavior, unfortunately, is more difficult than it seems. The most common approach assumes a random angle of tree fall (Maser and Trappe 1984, Rainville et al. 1985, McDade et al. 1990, Robison and Beschta 1990a, Van Sickle and Gregory 1990). Van Sickle and Gregory (1990) modeled the probability (P_s) of a tree entering the stream channel as:

$$P_s = \int_{a_s}^{180-a} f(a)da \qquad (2)$$

where a_s = $\sin^{-1}(z/h)$, z is the perpendicular downslope distance from standing tree to nearest channel boundary, h is the effective tree height, and $f(a)$ is the pattern of tree fall. Their integration of random fall direction yielded:

$$P_s = cos^{-1}\frac{(z/h)}{180} \qquad (3)$$

However, because of asymmetry in biomass distribution, differences in root support, and unpredictable disturbance patterns, some have questioned the randomness of treefall, especially when trees are in steep drainages and or immediately adjacent to the channel (Lienkaemper and Swanson 1987, Van Sickle and Gregory 1990). For example, when measuring the direction of windthrow in spruce-fir forests of Colorado, Veblen (1986) found that 95% of downed trees fell in an easterly direction, indicating the influence of strong westerly winds (similar to the results of Alexander and Buell (1955) and Schmid et al. (1985)). Along stream bottoms, snag dynamics are also complicated, so we were uncomfortable using either random or unimodal fall patterns. Unlike some modeling efforts, we had an available database on piece angle relative to stream location. Using this as a guide, we determined that along the reaches we observed, snags did not fall randomly but instead fit a trimodal distribution (figure 4). According to our samples,

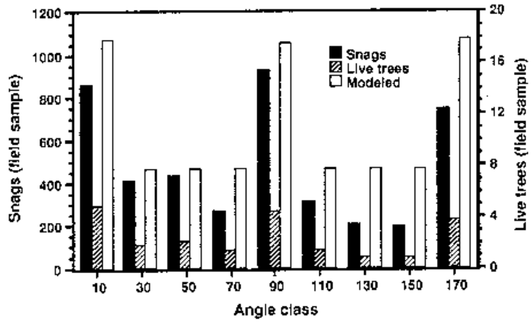

Figure 4. Distribution of angle-of-debris fall that was selected. The large woody debris (both downed logs and standing snags) and live tree categories reflect actual number of individuals (*n* = 4330 and 1310, respectively) measured from 13 streams in northwestern Wyoming. Model values represent those applied by CWD.

most snags fell in 1 of 3 directions (± 10°): towards the stream (0°); parallel to the stream (90°); or away from the stream (180°). Using a χ^2 test on a circular distribution (Zar 1984), our sample differed significantly from a random distribution for both live tree lean ($\chi^2 = 458.9$, $P < 0.001$) and LWD fall ($\chi^2 = 1338.6$, $P < 0.001$) angle distributions, so we biased the subroutine that determined the angle of fall to reflect this pattern. While the angles of fall were strongly biased around 0, 90, and 180°, it is possible to fall between these values. 0° and 180° were assigned 17.8% of the grand total, 90° was given 17.6%, and the other six 20°-wide categories were each assigned 7.8%. On nonmeandering stream systems (those with channel sinuosity < 1.5 (Ritter 1986)), a snag falling within an angle of $0° \leq \theta \leq 90°$ was considered *potentially* capable of delivering LWD to the stream. Riparian LWD recruitment was then developed as a function of angle of snag fall, distance from the stream, and snag fragmentation patterns.

LWD Fragmentation

Dead trees fragment in a highly unpredictable manner. For example, if a snag has stood for a long time, some sections of the top are likely to have broken off. Other snags fracture only when they strike the earth) or other objects with further breakage occurring when the snag is struck (e.g., another piece of debris falling on it). Because we did not know the spatial location of any piece of LWD, we could not account for its fragmentation history. Therefore, we decided to completely fragment the stem immediately after it falls and consider no further breakage. The number of pieces formed and their lengths were estimated from distributions similar to those measured in the field for downed debris (see Appendix A, figure A3).

Redimensioning LWD

After fragmenting each snag, it is necessary to redimension all of the new pieces to allow for calculation of piece volume. To do this, we applied a stem taper equation[1] modified from Czaplewski et al. (1989):

$$D = \hat{d}_1 (c_1 + c_2 DBH) \tag{4}$$

where c_1 and c_2 are species-specific coefficients and:

$$\hat{d}_1 = DBH\sqrt{b_1\left(\frac{h}{H}-1\right)+b_2\left(\frac{h^2}{H^2}-1\right)+b_3\left(a_1-\frac{h}{H}\right)^2 I_1+b_4\left(a_2-\frac{h}{H}\right)^2 I_2} \tag{4a}$$

For Equation 4a, b_1, b_2, b_3, and b_4 are species-specific regression coefficients, h is the height at the predicted diameter, H is the total tree height, a_i are species-specific join points (i = 1 (upper), i = 2 (lower)), and $I_i = 1$ if $h/H < a_i$, otherwise $I_i = 0$. These equations provided the end diameters for the newly created pieces of LWD. Subtracting the location of breaks from the old end positions provided the new piece lengths. To calculate individual piece volume, we applied a geometric volume equation (Lienkaemper and Swanson 1987, Richmond and Fausch 1995):

$$Volume = \frac{\pi\left(D_1^2 + D_2^2\right)L}{8} \tag{5}$$

where D_1 is the top and D_2 is the bottom end diameters and L is piece length.

Selection of LWD Pieces to Enter Stream

Once CWD redimensions each piece, it selects those that enter the bankfull channel. Because the distance from the stream ($DIST_s$), elevation of the snag relative to bankfull channel ($ELEV$), angle of stem fall (θ_H), and length (L) of the individual pieces of LWD are known, it is possible to calculate

[1] CWD versions before version 1.4 used Kozak et al. (1969) to predict stem taper. While more complicated to use, Czaplewski et al.'s (1989) taper equation is more accurate since it was derived from trees in Wyoming and Colorado for most species on the BTNF.

which pieces meet the recruitment criteria ($L \geq DIST_s$) with the following equation:

$$L \geq \left(\frac{DIST_s}{\cos\theta_H}\right)\left(\frac{1}{\cos\theta_v}\right) \quad (6)$$

where the elevational piece adjustment (θ_v) equals

$$\theta_v = \arctan\left(\frac{ELEV}{DIST_s}\right) \quad (6a)$$

If $DIST_s$ overlaps the distance from the piece by at least 1 m, the piece is delivered to the stream (figure 3). Since it was possible for a snag to fall across the stream and have pieces break off outside of the required bankfull zone, CWD was instructed to disregard those pieces.

Within-Stream LWD Attrition

To be most beneficial, a piece of riparian LWD should be retained within the active channel for extended periods of time. Retention is a function of stream width, flow characteristics, LWD size (especially length), and decay rates (Triska and Cromack 1980, Likens and Bilby 1982, Lienkaemper and Swanson 1987, Bilby and Ward 1989, McDade et al. 1990). Small pieces of LWD are often highly transient, which limits their value (Sedell et al. 1988, McDade et al. 1990). Large pieces are retained, on average, longer because of lower mobility and slower decay. LWD retention is related to length; the longer a piece is, the more likely it is to get wedged along the bank or aggregated with other debris. While seasonal floods, debris torrents, or channel shifts can eliminate more LWD than decay, decomposition is an important variable in determining piece residency. For example, decomposed logs are more susceptible to fragmentation, impacts from other falling trees, or bank shifts than structurally sound ones.

Since CWD does not explicitly model in-stream debris movement, our approach assumed that riparian LWD follows a long-term steady state (Froehlich 1973, Likens and Bilby 1982, Murphy and Koski 1989, Bragg and Kershner 1997) and that to do so, losses should roughly equal inputs in unmodified old-growth stands. For this paper, the volume of debris lost is a function of the initial quantity in the studied reach. The assumptions used to generate riparian LWD turnover rates are similar to those reported elsewhere (Murphy and Koski 1989, Bilby and Ward 1991, Maser and Sedell 1994). The following relationship describes this dynamic:

$$\textit{LWD load} = \textit{previous LWD} + \textit{new LWD} - \textit{LWD lost} \quad (7)$$

The volumetric turnover rate of LWD was then fixed as a constant ratio, which was applied during each delivery cycle. If losses exceeded recruitment, then the net riparian LWD volume decreased. While this generated a fluctuating LWD load, it implied nothing about specific piece attrition within size classes. However, further refinements to address piece demographics are possible since CWD output includes delivery by size class.

Field Sampling Results

Riparian Forest Conditions

All 13 stands sampled on the BTNF (table 2) were classified as subalpine fir-series habitat types (Steele et al. 1983). Engelmann spruce and subalpine fir dominated most riparian forests, although some plots (Adams Creek, Buck Creek, Blind Bull Creek, and the Hoback River) were predominantly blue spruce and/or Douglas-fir. Stand densities ranged from a minimum basal area of 14.2 to a maximum of 40.6 m^2/ha (mean = 25.3, standard deviation (SD) = 8.2). Stocking varied from a minimum of 182 trees/ha to a maximum of 655 trees/ha (mean = 373.5, SD = 141.7). While no age data were gathered, judging from tree size, most of these riparian stands likely exceeded 200 y. Since they were also selected for minimal human intervention, we felt they were representative of old-growth riparian spruce-fir forests in the central Rocky Mountains.

Riparian Forest LWD Conditions

Examination of riparian forest LWD found that most of this material was not visually identifiable to species because of decay and erosion (table 3). Since we were more concerned with LWD as a unit of volume, no further effort was made to identify

Table 2. Stand characteristics of sampled riparian forests[a] in northwestern Wyoming (standard deviations are in parentheses).

Stream	Habitat type[b]	Species composition	Basal area (m^2/ha)	Trees (per ha)	Plot volume (m^3/ha)	Mean DBH (cm)	Mean height (m)
Adams Creek	ABLA/PHMA	36% *Picea pungens* 35% *Pseudotsuga menziesii* 17% *Abies lasiocarpa* 11% *Pinus contorta* 1% *Pinus flexilis* 1% *Picea engelmannii*	14.2 (1.12)	243 (121)	129.9 (13.1)	23.4 (14.1)	15.6 (7.9)
Moose Gulch Creek	ABLA/ACRU	56% *Picea engelmannii* 42% *Abies lasiocarpa* 2% *Pinus contorta*	23.0 (0.61)	320 (79)	224.8 (10.0)	26.5 (14.7)	16.6 (9.6)
Murphy Creek	ABLA/ACGL	60% *Abies lasiocarpa* 28% *Picea engelmannii* 11% *Pseudotsuga menziesii*	17.8 (2.65)	240 (194)	157.6 (26.0)	25.3 (17.6)	13.3 (8.2)
Blind Bull Creek	ABLA/ACRU	47% *Picea pungens* 31% *Picea engelmannii* 16% *Abies lasiocarpa* 6% *Pinus contorta* 1% *Pseudotsuga menziesii*	32.5 (4.14)	435 (186)	300.7 (47.5)	26.8 (15.3)	15.9 (8.7)
Buck Creek	ABLA/PHMA	52% *Pseudotsuga menziesii* 28% *Picea pungens* 16% *Abies lasiocarpa* 2% *Pinus flexilis* 1% *Picea engelmannii* 1% *Populus* spp.	15.4 (1.57)	182 (86)	136.3 (17.2)	29.7 (14.0)	19.1 (8.9)
Dry Lake Creek	ABLA/VASC-VASC	56% *Picea engelmannii* 28% *Abies lasiocarpa* 14% *Pinus contorta* 2% *Picea pungens* 1% *Pinus flexilis*	33.2 (1.05)	655 (197)	277.3 (15.7)	22.6 (11.6)	15.0 (6.3)
South Fork Gypsum Creek	ABLA/ARCO-SHCA	44% *Picea engelmannii* 30% *Picea pungens* 17% *Abies lasiocarpa* 9% *Pseudotsuga menziesii*	30.8 (2.67)	423 (178)	315.2 (29.7)	26.8 (14.5)	19.4 (9.1)

Table 2. (Cont'd.)

Stream	Habitat type[b]	Species composition	Basal area (m^2/ha)	Trees (per ha)	Plot volume (m^3/ha)	Mean DBH (cm)	Mean height (m)
Sheep Creek	ABLA/ACRU	72% *Picea engelmannii* 27% *Abies lasiocarpa* 1% *Pinus contorta*	40.6 (1.07)	392 (118)	489.4 (24.0)	30.9 (19.1)	20.8 (11.4)
Willow Creek	ABLA/VASC-VASC	36% *Abies lasiocarpa* 35% *Picea engelmannii* 25% *Pinus contorta* 4% *Picea pungens*	26.8 (1.17)	530 (94)	252.7 (13.5)	22.6 (11.5)	17.1 (7.0)
Blackrock Creek	ABLA/JUCO	55% *Picea engelmannii* 38% *Abies lasiocarpa* 4% *Pinus contorta* 2% *Picea pungens* 2% *Populus* spp.	17.1 (1.71)	537 (438)	116.5 (10.8)	18.6 (7.9)	12.8 (4.7)
Ditch Creek	ABLA/ACRU	83% *Picea engelmannii* 11% *Abies lasiocarpa* 6% *Alnus tenuifolia* 1% *Pinus contorta*	19.4 (2.95)	213 (174)	185.1 (30.2)	30.2 (15.8)	18.9 (8.0)
Hoback River	ABLA/ACRU	47% *Picea pungens* 28% *Abies lasiocarpa* 14% *Picea engelmannii* 11% *Pinus contorta* 1% *Pinus flexilis*	30.7 (3.57)	372 (188)	334.6 (45.7)	28.0 (16.3)	19.4 (9.2)
Mosquito Creek	ABLA/ACRU	66% *Picea engelmannii* 27% *Abies lasiocarpa* 6% *Pinus contorta* 1% *Alnus tenuifolia*	27.5 (2.02)	313 (65)	290.9 (26.6)	28.9 (16.9)	18.2 (9.8)

[a] *Only trees > 10 cm DBH were sampled.*

[b] *Predominant plot habitat type, taken from Steele et al. (1983). ABLA* = Abies lasiocarpa; *ACRU* = Actaea rubra; *ACGL* = Acer glabrum; *PHMA* = Physocarpus malvaceus; *VASC* = Vaccinium scoparium; *ARCO* = Arnica cordifolia; *SHCA* = Shepherdia canadensis; *JUCO* = Juniperus communis.

Table 3. Large woody debris (LWD) inventory of sampled riparian forests in northwestern Wyoming (standard deviations are in parentheses).

Stream	LWD species composition	Mean large-end diameter (cm)	Mean piece length (m)	Mean piece volume (m^3)	LWD volume (m^3/ha)	Pieces LWD (per ha)
Adams Creek	36% *Abies lasiocarpa*	23.1	5.7	0.23	93.6	410
	26% Unknown spp.	(13.3)	(5.8)	(0.36)	(11.7)	(213)
	22% *Pseudotsuga menziesii*					
	11% *Picea pungens*					
	3% *Pinus contorta*					
	2% *Populus* spp.					
Moose Gulch Creek	62% Unknown spp.	24.5	6.3	0.31	190.1	614
	26% *Abies lasiocarpa*	(10.5)	(6.0)	(0.48)	(19.0)	(196)
	10% *Picea engelmannii*					
	1% *Pinus contorta*					
	1% *Populus tremuloides*					
	1% *Alnus tenuifolia*					
Murphy Creek	57% Unknown spp.	27.7	5.0	0.42	113.2	268
	28% *Abies lasiocarpa*	(17.6)	(4.9)	(0.90)	(19.7)	(207)
	9% *Picea engelmannii*					
	6% *Pseudotsuga menziesii*					
Blind Bull Creek	59% Unknown spp.	19.3	5.1	0.16	113.3	715
	27% *Abies lasiocarpa*	(9.6)	(4.9)	(0.29)	(10.1)	(196)
	6% *Picea engelmannii*					
	6% *Pinus contorta*					
	3% *Picea pungens*					
Buck Creek	62% Unknown spp.	22.3	4.2	0.16	57.2	367
	13% *Abies lasiocarpa*	(10.2)	(3.8)	(0.22)	(8.3)	(288)
	12% *Pseudotsuga menziesii*					
	5% *Populus* spp.					
	4% *Picea pungens*					
	2% *Juniperus scopulorum*					
	1% *Picea engelmannii*					
Dry Lake Creek	69% Unknown spp.	22.9	5.9	0.28	149.2	537
	21% *Abies lasiocarpa*	(12.3)	(5.8)	(0.68)	(14.2)	(250)
	6% *Pinus contorta*					
	3% *Picea engelmannii*					
South Fork Gypsum Creek	66% Unknown spp.	21.9	6.1	0.27	217.4	807
	13% *Picea engelmannii*	(11.2)	(6.3)	(0.65)	(22.6)	(325)
	10% *Abies lasiocarpa*					
	5% *Picea pungens*					
	3% *Populus tremuloides*					
	2% *Pseudotsuga menziesii*					

Table 3. (Cont'd.)

Stream	LWD species composition	Mean large-end diameter (cm)	Mean piece length (m)	Mean piece volume (m^3)	LWD volume (m^3/ha)	Pieces LWD (per ha)
Sheep Creek	56% Unknown spp. 22% *Picea engelmannii* 21% *Abies lasiocarpa* 1% *Pinus contorta*	23.7 (14.2)	5.9 (6.4)	0.36 (0.86)	206.9 (26.7)	582 (332)
Willow Creek	55% Unknown spp. 27% *Pinus contorta* 14% *Abies lasiocarpa* 4% *Piçea engelmannii*	19.9 (7.5)	6.1 (6.3)	0.19 (0.28)	171.3 (12.3)	917 (380)
Blackrock Creek	71% Unknown spp. 20% *Abies lasiocarpa* 5% *Picea engelmannii* 2% *Pinus contorta* 1% *Picea pungens* 1% *Populus tremuloides*	20.6 (9.5)	4.2 (4.4)	0.17 (0.38)	81.2 (11.0)	490 (359)
Ditch Creek	46% Unknown spp. 23% *Picea engelmannii* 20% *Abies lasiocarpa* 6% *Alnus tenuifolia* 4% *Populus* spp.	22.1 (12.0)	5.1 (5.5)	0.23 (0.44)	84.9 (19.2)	372 (423)
Hoback River	44% Unknown spp. 26% *Pinus contorta* 19% *Abies lasiocarpa* 10% *Picea pungens* 1% *Picea engelmannii*	20.7 (9.2)	10.1 (7.1)	0.33 (0.51)	135.4 (10.9)	412 (176)
Mosquito Creek	48% Unknown spp. 30% *Abies lasiocarpa* 19% *Picea engelmannii* 4% *Pinus contorta*	27.7 (10.5)	5.0 (5.5)	0.42 (0.52)	113.2 (12.4)	268 (167)

the species. Most pieces averaged 4.2 m (SD = 1.5) in length and 22.8 cm (SD = 2.6) in large-end diameter, although this varied by site (table 3). LWD volume ranged from a minimum of 57.2 to a maximum of 217.4 m^3/ha (mean = 132.8, SD = 50.9). This is similar to LWD loads reported for spruce-fir forests in other regions, but differs from other cover types (table 4). Ultimately, riparian forest LWD volume is limited by the productivity of the spruce-fir forests in this area, which in turn are controlled by stand age, precipitation, growing season length, and disturbance regime.

Table 4. Forest large woody debris (LWD) loads by area and forest type. Unless provided by the original authors, we used a conversion factor of 0.2 Mg/m^3 (Harmon et al. 1986) to convert LWD volume into LWD biomass (note that researchers define LWD differently).

Predominant forest type	Location[a]	Volume (m^3/ha)	LWD biomass (Mg/ha)[b]	Minimum piece dimensions	Source[c]
Engelmann spruce-subalpine fir	Bridger-Teton N.F., Wyoming	132.8 (57.2 - 217.4)[d]	26.6 (11.4 - 43.5)[d]	1 m length 10 cm diameter	this study
Engelmann spruce-subalpine fir	Gallatin N.F., Montana	79.8	16.0	no length 7.5 cm diameter	1
Engelmann spruce-subalpine fir	Nez Perce N.F., Idaho	117.5	23.5	no length 7.5 cm diameter	1
Engelmann spruce-subalpine fir	Dear Lodge N.F., Montana	135.7	27.1	no length 7.5 cm diameter	1
Engelmann spruce-subalpine fir	Flathead N.F., Montana	190.3	38.1	no length 7.5 cm diameter	1
Engelmann spruce-subalpine fir	Clearwater N.F., Idaho	97.3	19.5	no length 7.5 cm diameter	1
Engelmann spruce-subalpine fir	Colville N.F., Washington	255.4	51.1	no length 7.5 cm diameter	1
Engelmann spruce-subalpine fir	northern Idaho	131.5	26.3	no length 7.5 cm diameter	1
Mixed conifers	Sequoia N.P., California	311.1	89.6*	1.5 m length > 15 cm diameter	2
Spruce-fir	not stated	416	97*	no length- only logs 7.5 cm diameter	3
Douglas-fir	Coastal Range, Oregon	379	95	10 cm diameter	4
Douglas-fir	Cascades Mtns., Washington	544	121	10 cm diameter	4
Douglas-fir	Cascade Mtns., Oregon	594	136	10 cm diameter	4
Hemlock-hardwood	northern Michigan-northern Wisconsin	121.3 (55.1 - 207.2)[d]	24.3 (11.0 - 41.4)[d]	no length 20 cm diameter	5

[a] *N.F. = National Forest, N.P. = National Park.*

[b] ** = values provided by the original study, using their own estimates of LWD density.*

[c] *Source codes: 1 = Brown and See (1980), 2 = Harmon et al. (1987), 3 = Harmon et al. (1986), 4 = Spies et al. (1988), 5 = Tyrell and Crow (1994).*

[d] *Numbers in parentheses represent the minimum and maximum values reported by that study.*

Stream LWD Conditions

Very few pieces of riparian LWD were identified to species (typically 20% to 30%), which is expected because moving water rapidly removes bark and other distinguishing characteristics. Mean large-end diameters did not vary appreciably from those found in adjacent riparian forests. Unlike some studies (Bisson et al. 1987, Bilby and Ward 1989, Nakamura and Swanson 1994) that noted a positive shift in mean piece length with increasing stream bankfull width, no such trend was apparent in our data (table 5). Riparian LWD volume varied from a low of 4.8 up to 54.5 m^3/100 m reach (mean = 19.4, SD = 14.3). Table 6 compares this study with other work on riparian LWD.

Table 5. Large woody debris (LWD) inventory of sampled streams in northwestern Wyoming (standard deviations are in parentheses).

Stream	LWD species composition	Mean large-end diameter (cm)	Mean piece length (m)	Mean piece volume (m^3)	LWD volume[a] (m^3/100 m)	Pieces per 100 m[a]	Volume[a] (m^3/m^2)
Adams Creek	66% Unknown spp. 18% *Abies lasiocarpa* 5% *Pseudotsuga menziesii* 6% *Populus* spp. 2% *Picea pungens* 2% *Picea engelmannii* 1% *Salix* spp.	19.2 (9.5)	4.1 (4.2)	0.18 (0.39)	8.7	48	0.029
Moose Gulch Creek	88% Unknown spp. 6% *Abies lasiocarpa* 5% *Picea engelmannii* 1% *Alnus tenuifolia*	24.1 (12.2)	4.3 (5.1)	0.27 (0.60)	21.0	76	0.062
Murphy Creek	78% Unknown spp. 17% *Picea engelmannii* 6% *Abies lasiocarpa*	26.3 (19.1)	4.3 (6.5)	0.64 (1.93)	27.5	43	0.045
Blind Bull Creek	67% Unknown spp. 14% *Abies lasiocarpa* 13% *Picea pungens* 3% *Picea engelmannii* 3% *Pinus contorta*	24.2 (13.3)	4.8 (4.6)	0.41 (0.88)	15.4	37	0.027
Buck Creek	76% Unknown spp. 12% *Abies lasiocarpa* 6% *Picea pungens* 4% *Populus* spp. 2% *Pseudotsuga menziesii*	23.0 (10.7)	4.6 (4.6)	0.25 (0.56)	16.8	66	0.035
Dry Lake Creek	85% Unknown spp. 10% *Abies lasiocarpa* 2% *Picea engelmannii* 2% *Pinus contorta*	20.6 (10.8)	3.9 (3.7)	0.18 (0.41)	8.6	48	0.016
South Fork Gypsum Creek	81% Unknown spp. 14% *Picea engelmannii* 3% *Abies lasiocarpa* 1% *Pseudotsuga menziesii*	25.7 (13.9)	5.8 (6.2)	0.46 (1.04)	54.5	118	0.045
Sheep Creek	76% Unknown spp. 14% *Abies lasiocarpa* 10% *Picea engelmannii*	21.5 (11.1)	3.6 (3.7)	0.21 (0.41)	13.5	66	0.029

Correlation of Stream Size with LWD Loading

Generally, as stream size increases, its hydraulic potential during high flows also increases, resulting in a greater capacity of that flow to attenuate LWD (Bilby and Ward 1989). It is unlikely that under undisturbed conditions reach LWD load ever reaches zero with increasing width because there are always locations along the edge of the channel capable of debris retention. Figure 5 details the relationship between LWD load and mean bankfull width. An exponential function fit the LWD debris load suitably ($R^2 = 0.326$):

$$VM2 = 0.0561e^{-0.0843BFW} \qquad (8)$$

where *BFW* is the mean bankfull width of that particular reach. This corresponds with the work of others who found riparian LWD loads inversely

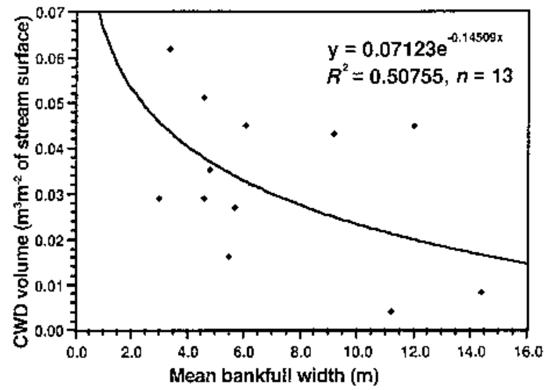

Figure 5. Trend between mean bankfull width and large woody debris volume per m² of stream surface area. The negative exponential curve reflects the increased transport power and more open forests of larger streams sampled in the Bridger-Teton National Forest.

Table 5. (Cont'd.)

Stream	LWD species composition	Mean large-end diameter (cm)	Mean piece length (m)	Mean piece volume (m^3)	LWD volume[a] (m^3/100 m)	Pieces per 100 m[a]	Volume[a] (m^3/m^2)
Willow Creek	71% Unknown spp. 17% *Abies lasiocarpa* 6% *Picea engelmannii* 6% *Pinus contorta*	21.0 (10.3)	5.9 (6.0)	0.27 (0.64)	23.4	88	0.051
Blackrock Creek	74% Unknown spp. 16% *Picea engelmannii* 10% *Abies lasiocarpa*	24.7 (11.2)	4.4 (3.4)	0.24 (0.30)	6.5	27	0.004
Ditch Creek	72% Unknown spp. 20% *Alnus tenuifolia* 8% *Picea engelmannii*	18.2 (12.8)	2.8 (3.6)	0.20 (0.39)	4.8	24	0.004
Hoback River	83% Unknown spp. 9% *Picea pungens* 4% *Abies lasiocarpa* 2% *Pinus contorta* 1% *Picea engelmannii*	21.0 (11.7)	5.4 (5.4)	0.31 (0.71)	11.9	38	0.008
Mosquito Creek	83% Unknown spp. 11% *Picea engelmannii* 5% *Abies lasiocarpa* 1% *Pinus contorta*	21.8 (13.3)	4.1 (5.1)	0.29 (0.68)	39.8	140	0.043

[a] *Within-stream estimate of standard deviation is unavailable because these parameters were measured as a single unit without replicates.*

Table 6. Stream large woody debris (LWD) loads for largely undisturbed forests by region and cover type. Values are not directly comparable because of differences in definition of riparian LWD. Biomass conversion assumes 0.2 Mg/m³ (Harmon et al. 1986).

Forest type	Location[a]	Volume[a]	LWD biomass[b]	Piece density[c]	Minimum dimensions	Source[d]
Engelmann spruce-subalpine fir	B.T.N.F., Wyoming	19.4 (A) (4.8 - 54.5)[e]	3.9 (C) (1.0 - 10.9)	63.0 (F) (24 - 140)	1 m length 10 cm diameter	this study
Engelmann spruce-subalpine fir	north central Colorado	13.3 (A) (6.6 - 27.1)	2.7 (C) (1.3 - 5.4)	43.4 (F) (18 - 64)	1 m length 10 cm diameter	1
Spruce-lodgepole pine	Idaho	—	7 (D)	—	> 10 cm diameter	2
Mixed conifers	northeast Oregon	140 (B)	28 (C)	390 (G)	1 m length 10 cm diameter	3
Mixed conifers	northeast Oregon	145 (B)	29 (C)	450 (G)	1 m length 10 cm diameter	3
Mixed conifers	southeast Washington	195 (B)	39 (C)	250 (G)	1 m length 10 cm diameter	3
Mixed conifers	Stanislaus N.F., California	136 (B)	27.2 (C)	17.8 (F)	1 m length 10 cm diameter	4
Sitka spruce-western hemlock	southeast Alaska	58 (A) (36 - 100)	11.6 (C) (7.2 - 20)	33 (F) (25 - 42)	1.5 m length 20 cm diameter	5
Douglas-fir	Willamette N.F., Oregon	478 (B) (230 - 750)	191.2 (C) (92 - 300)	—	1.5 m length 10 cm diameter	6
Mixed conifers	southwest British Columbia	43.2 (A) (16.6 - 85.0)	234.5 (E) (74 - 448)	42.0 (F) (26 - 60)	2 m length 10 cm diameter	7
eastern hemlock-hardwoods	Blue Ridge Mtns., southeastern U.S.	21.9 (A)	8.6 (C)	51.4 (F)	1.5 m length 10 cm diameter	8

[a] *Volume codes: A = m³/100 m stream reach, B = m³/ha.*

[b] *LWD biomass codes: C = Mg/100 m stream reach, D = kg/m², E = Mg/ha.*

[c] *Piece density codes: F = pieces/100 m stream reach, G = pieces/ha.*

[d] *Source codes: 1 = Richmond and Fausch (1995), 2 = Triska and Cromack (1980), 3 = Carlson et al. (1990), 4 = Ruediger and Ward (1996), 5 = Robison and Beschta (1990a), 6 = Lienkaemper and Swanson (1987), 7 = Fausch and Northcote (1992), 8 = Hedman et al. (1996)*

[e] *Numbers in parentheses represent the minimum and maximum values reported by that study.*

related to stream dimensions (Bilby and Ward 1989, Robison and Beschta 1990b, Bilby and Ward 1991, Gippel 1995, Richmond and Fausch 1995). Bilby and Ward (1989) found a similar decreasing pattern between piece frequency and stream size in the Pacific Northwest, while Keller and Swanson (1979) noted a decline in LWD biomass (in kg/m) with increasing channel width.

A Simulated Case Study: Dry Lake Creek, Wyoming

Perhaps the best way to exhibit the potential of CWD is through simulation[2] of an undisturbed old-growth riparian stand. Since FVS can generate forest management practices, we simulated a clearcut (in year 50) of the initial old-growth stand to evaluate the impact of human disturbance on LWD dynamics (the clearcut scenario). FVS then generated output files for each scenario that CWD processed into 300 y debris dynamics. The results in figures 6 to 8 represent 10 replicate runs.

Undisturbed riparian forests along Dry Lake Creek are predicted to deliver about 2.6 m^3 (SD = 1.33) of LWD/100 m reach every 10 y (figure 6*a*). Since we know the current in-stream LWD load (8.6 m^3/100 m reach, table 5), this suggests that Dry Lake Creek experiences a riparian LWD turnover rate of 20% to 60% per decade, assuming the inventory of 1995 reflects a long-term steady-state riparian LWD load. Other authors (Murphy and Koski 1989, Bilby and Ward 1991, Maser and Sedell 1994) have noted similar riparian LWD turnover rates.

Clearcutting has a different impact on riparian LWD dynamics. During the first 50 y of the simulation (figure 6*b*), LWD recruitment for the preharvest stand did not differ significantly from the undisturbed stand (the peak in year 50 resulted from harvest-accelerated snag failure). After clearcutting occurs, delivery declined to zero by year 60 and stayed negligible over the next 60 y. Post-clearcut LWD recruitment did not reach no-harvest levels until 200+ y after the disturbance.

The cumulative effect of changes in recruitment can be seen in figure 7. The old-growth scenario steadily added LWD, reaching 79.4 m^3/100 m over the simulation period (figure 7*a*). The clearcut reach, however, delivered only 40.7 m^3/100 m, approximately half the volume it would have accumulated under an undisturbed scenario. Figure 7*b* shows how the cumulative recruitment following harvesting differed for 150+ y after the clearcut; its trajectory flattened to virtually zero for almost a century. The difference in recruitment resulted from the naturally slow recovery of the postharvest riparian stand and the absence of post-event snags that could have provided, however reduced, LWD delivery during stand regrowth. Grette (1985) noted similar trends in LWD loads measured in postharvest watersheds in western Washington.

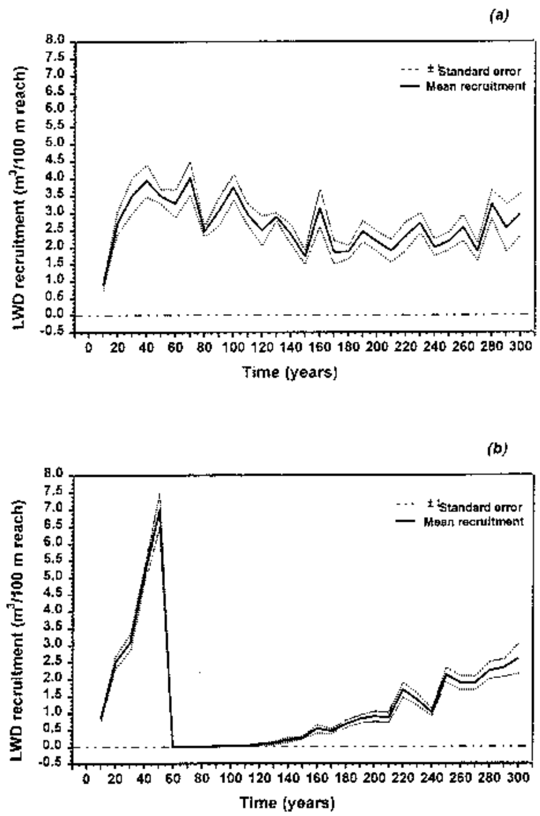

Figure 6. Large woody debris recruitment predicted by CWD over the 300 y simulation period. Undisturbed riparian forests along Dry Lake Creek (*a*) delivered almost 2.6 m^3/100 m reach/10 y cycle, while after clearcutting occurs (*b*), the simulated stand averaged less than 1.4 m^3/100 m reach. The sharp, relatively short-term oscillations apparent for both scenarios likely resulted from FVS- and CWD-programming effects rather than ecological processes.

[2] *CWD version 1.3 was used for this case study, which is only cosmetically different from version 1.4.*

The net impact of these scenarios on in-stream LWD loads is shown in figure 8. Using our assumption of in-stream LWD attrition (see Bragg and Kershner 1997), the undisturbed conditions achieved a relatively constant LWD stocking of 8.6 $m^3/100$ m reach. The volumes delivered under this scenario were consistent from cycle to cycle (SD = 1.89). Clearcutting loads averaged only 4.6 $m^3/100$ m reach and lingered at < 15% of undisturbed levels for several consecutive decades. Under certain conditions, both LWD delivery and in-stream loads may fall to zero with potentially significant impacts on stream habitat for decades following the clearcutting of riparian forests.

Validation of Model

Without detailed, long-term surveys of LWD recruitment, it is difficult to evaluate the performance of CWD. Typically, we hope for an approximation of known (although instantaneous) conditions of our studied reaches. To this end, we have several measures with which to compare model behavior against field conditions. Figure 9 lists 2 tangible attributes of riparian LWD measured in Dry Lake Creek: piece diameter and length. The

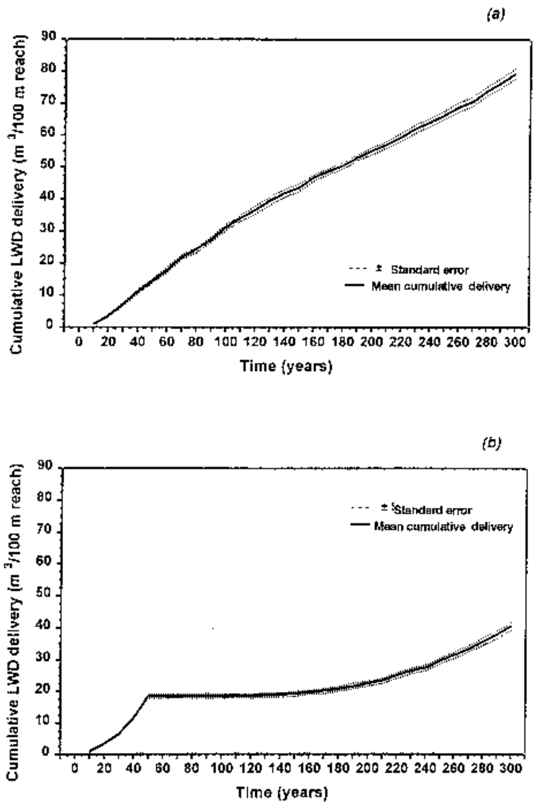

Figure 7. Cumulative large woody debris delivery for Dry Lake Creek, WY, under undisturbed (*a*) and clearcut (*b*) simulations. Both scenarios developed similar recruitment patterns until clearcutting occurred in year 50, and they remained different throughout the rest of the simulation.

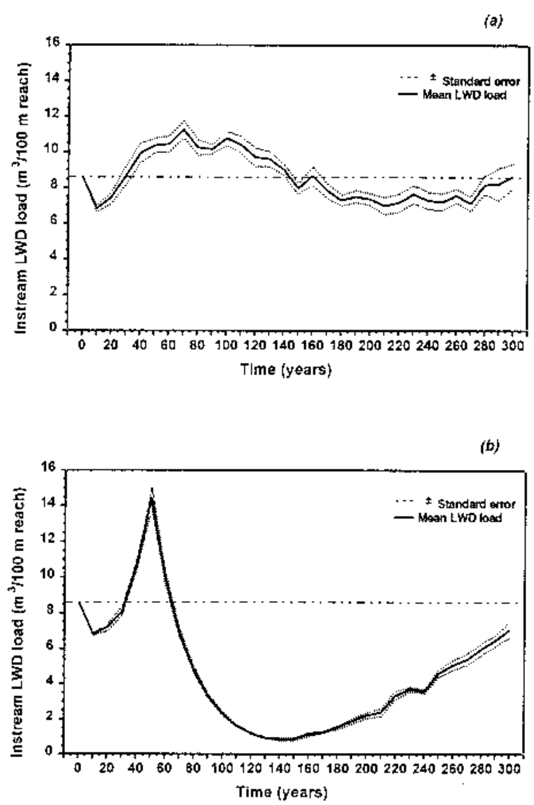

Figure 8. Calculated in-stream large woody debris (LWD) load for Dry Lake Creek, WY, under undisturbed (*a*) and clearcut (*b*) simulations. Clearcutting occurred in year 50. Less than 70 y later riparian LWD loads were forecast to decline to < 15% of the long-term undisturbed riparian LWD average.

top graph (*a*) compares predicted piece large-end diameter against that inventoried in 1995. Some significant differences existed for diameter; however, the predicted distribution is averaged over a 300 y period while the field data represents that sampled in the stream at a particular point in time. The apparent shift in piece diameter in figure 9*a* could have resulted from the maturation and concurrent increase in tree size of the riparian forest, which in turn generated larger pieces of debris.

More importantly, predicted and observed piece length data show much better agreement. With the exception of the smallest (1 to 2 m) and largest (18 to 24 m) length classes, piece length patterns are

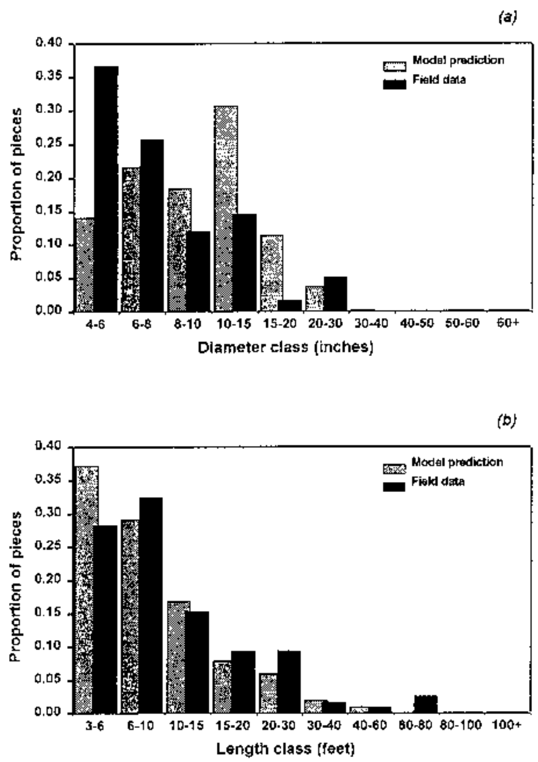

Figure 9. Initial validation of large woody debris (LWD) modeling results using recruited piece diameter (*a*) and piece length (*b*). The discrepancies between field data and model predictions for piece diameter probably resulted from attrition of LWD once in the channel and the maturation and concurrent increase in tree size of the riparian forests during the simulation period. More importantly, a better fit of the piece length data indicates realistic projections of riparian LWD recruitment patterns.

generally similar. The model likely over predicts the shortest pieces because of the tendency of small debris to be flushed out quickly. Mean predicted piece length (3.2 m, SD = 0.6) is similar to that measured in Dry Lake Creek (3.9 m, SD = 3.7, see table 5). Accurate representation of piece length patterns is especially critical because of the relationship between debris length and in-stream retention.

Discussion

As with any model that is partially derived from empirical data, CWD's predictions are sensitive to initial conditions and subject to considerable variance from one reach to another. However, the information generated does not exceed the natural limits involved and indicates which factors and processes are most important in determining patterns of LWD recruitment.

Riparian forest conditions heavily influence riparian LWD loading. The more mature and intact the adjacent riparian forest is, the greater the likelihood of sustained LWD delivery. Streams that have forested cover to bankfull width also contribute significant new LWD. The likelihood of delivery declines steeply with increasing distance to the stream (McDade et al. 1990, Robison and Beschta 1990a, Van Sickle and Gregory 1990), making the timber adjacent to the stream the most vital reserve of LWD. Successional status of the riparian forest has a multifaceted impact on in-stream LWD volumes. Although vigorous early successional stands experience greater mortality rates from self-thinning, they produce only small dead trees and hence smaller pieces of LWD, which can be quickly moved downstream. Old-growth stands, on the other hand, generate fewer snags for recruitment, but those created are often large and difficult to flush out. Old-growth may also be more susceptible to some catastrophic disturbances (Schmid and Hinds 1974, Romme 1982, Holsten et al. 1991, Everham and Brokaw 1996), thereby increasing the chance that extensive volumes of material can be added periodically. Wider floodplains and sparser vegetation along larger and, in our study, lower elevation streams contributed significantly to lower riparian LWD loads. Stream size is also responsible for much of the difference in LWD loading; larger streams, especially during high-water events have greater volumes of water flowing through them, providing the force to remove even the largest pieces of LWD.

While this study deals with volumetric measures of LWD, not all similar volumes have identical qualities. Because of their permanence, large pieces of LWD are more valuable than smaller, more ephemeral ones (Sedell et al. 1988, McDade et al. 1990). Large debris can easily span the small streams we sampled, bisecting the flow and trapping smaller pieces as they are washed into the superstructure. This newly imbedded matrix then traps smaller and smaller debris until very fine particles are trapped, leading to the accumulation of considerable amounts of sediment behind these debris dams (Marston 1982, Megahan 1982). On the downstream side of debris dams, water cascading over the dam quickly forms plunge pools and other scour-related structures that can provide critical habitat for many species. These debris dams can last for many years before decay and flowing water gradually erode away their structural integrity, or they can fail rapidly if high water or human actions weaken them. Turnover rates for small pieces are likely to be rapid in all but the smallest flows, while large pieces can persist for extended periods even in large rivers. Therefore, a stream with many small pieces is less structurally productive because of debris instability, while a stream with a few large pieces will have a value disproportionate to the abundance of LWD.

Watershed-Scale Applications of CWD

Application of CWD is adaptable to provide watershed-scale analysis of riparian LWD dynamics. Because small tributaries in many regions flow through continuous forest, they are vital contributors to the structural and functional characteristics of distant ecosystems (Minckley and Rinne 1985, Maser and Sedell 1994). Since these areas are heavily forested, they experience significant natural and human disturbance, which in turn affects the recruitment patterns of LWD (Bragg 1997). It should be possible to simulate an entire watershed (one 100 m reach at a time) and, using some assumptions on in-stream LWD attrition, predict how much debris each tributary contributes to the larger downstream flows. Different watershed-level timber harvests or natural disturbance regimes can then be applied to the tributary, allowing for assessment of large-scale impacts on systems that may not have otherwise been considered.

Conclusions

Pairing a forest growth and yield simulator with a riparian LWD recruitment model shows considerable promise for projecting the influence of a range of riparian forest management activities. As expected, riparian LWD recruitment depends heavily on the factors affecting the adjacent forest. Old-growth stands, with their abundance of large trees, delivered more and larger woody debris than a comparable reach stocked with younger, smaller individuals arising after a disturbance. CWD appears to do a good job generating recruitment patterns, debris loads, and other long-term dynamics. While reliable field validation will take years, preliminary evidence suggests CWD follows expected patterns. Improvement of some of the assumptions in this paper (e.g., stream LWD attrition over time) and more field data should improve our ability to predict stream response to changes in riparian zone management.

Predicting LWD recruitment using FVS and CWD can help develop strategies to remediate streams lacking LWD or can determine the potential effects of management activities on riparian zones. CWD provides forest managers and aquatic biologists with a tool to help understand the implications of forest structure and dynamics on riparian processes. The ability to customize both FVS and CWD for local conditions and management objectives provides managers with the flexibility to anticipate changes initiated by different treatments before implementing them in the field.

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Appendix A: User's Guide to the CWD Post-Processor (version 1.4)

Preface

CWD has been a work-in-progress for several years now, and as with all technology, staying on the cutting edge is virtually impossible. The Forest Vegetation Simulator (FVS) has evolved since this project began, and since the CWD post-processor is at the mercy of FVS development, it is easy to fall behind the curve. We urge caution in application of CWD. We have written this user's guide as a blueprint for those interested in using CWD to investigate the ecological impacts of various treatments on riparian large woody debris (LWD) recruitment.

—D.C.B., J.L.K., D.W.R.

Where to Get CWD and FVS

The executable file for CWD, associated model default file, and a digital version of this documentation are available from the primary author (D.C. Bragg) or the USFS Fish Ecology Unit (*http://www.fs.fed.us/biology/fishecology*). CWD is available as a self-extracting Zip™ file that creates its own subdirectory (default = C:\CWD1_4) on your hard drive. FVS files and documentation can be downloaded for free from:

http://www.fs.fed.us/fmsc/fvs_software.htm

Preliminary Steps to Run CWD

CWD is a riparian LWD recruitment model that predicts the amount of debris delivered to the bankfull channel as determined by forest dynamics generated with FVS (version 6.1). We assume some level of proficiency with FVS in the design of this user's guide. Contact the USDA Forest Service Timber Management group if specific questions arise in the operation of FVS. An example of a FVS keyword file (the one used to generate the tree list file for this report) is in Bragg (1997). Teck et al. (1997) also provides good examples of other work done with FVS, and valuable information can be found in Wykoff et al. (1982) and other Prognosis references.

CWD has largely been written in standard (ANSI) Fortran 90 code for MS-DOS™ (or in a MS-DOS shell sponsored by Windows™ 3.x, 95, or 98). Several files are necessary for successful operation of CWD:

- CWD1_4.EXE (executable file that processes the data)
- DEFAULT1.CWD (data file containing CWD default parameters)
- FVS tree list file (individual tree list file generated by FVS)

DEFAULT1.CWD *must* be in the same subdirectory as CWD1_4.EXE, while the FVS tree list file can be in any locatable subdirectory. The FVS tree list file *must* meet the following formats to be incorporated by CWD. The tree list file needs to be either space or comma delimited, with *no* text headers. The text header option can be turned off when creating the FVS tree list file (see Teck (1995) for the fields to alter on the TREELIST keyword) or deleted manually. FVS tree list files produce a series of tree records detailing the information tracked by each representative tree used to create the simulation

Table A1. Forest Vegetation Simulator (FVS) tree list output file formatting. FVS version 6.2 tree list output code is different and will not work with CWD.

Data type	Description	Use (yes/no)
character	tree number	no
integer	FVS tree index	no
integer	FVS species number	yes
integer	point number	no
real	mortality per acre	yes
real	current DBH	yes
real	diameter increment	no
real	current height	yes
real	height increment	no
integer	crown ratio code	no
integer	crown ratio (percent)	no
real	basal area percentile	no
integer	tree class	no
real	total cubic foot volume	no
real	merchantable cubic foot volume	no
real	merchantable board foot volume	no
integer	truncated height	no
integer	cycle number	yes
integer	regeneration code	no
integer	miscellaneous codes	no

(table A1). It is possible to use other models to create a tree list file acceptable to CWD, assuming identical formatting and the same type of information. If this is done, keep in mind that FVS tracks trees as representative individuals on an acre of land, so that mortality represents a fraction of that record per acre. Also note that CWD assumes a 10 y interval for its cyclic time step. CWD requires that English units will be used for *all* parameters because it was developed to smoothly integrate with FVS, which uses English units of measure. However, most scientific literature uses the metric system (including this paper). Table A2 provides a measurement unit conversions.

Introductory Screens

Once all files are available, begin execution by typing CWD at the DOS prompt of the appropriate subdirectory. As CWD loads, the first screen identifies the program and the version (figure A1). The version number is critical information as updates of the CWD post-processor are developed as new versions of FVS become available. We also expect to develop CWD versions for other regions. Version 1.4 is designed to work with the Utah and Teton variants of FVS (version 6.1 tree list file format) *only*. Use of version 1.4 with tree list files from other variants is *not advised* because of differences in species codes for early (version 6.1 and older) variants. Old versions of FVS (Prognosis) may have unsuitable formatting to be read by CWD (see previous section for required tree list input file format). The tree list output file of FVS version 6.2 has some new columns, and lacks other important data, and cannot be interpreted by CWD version 1.4. To continue past the introductory screen, press <ENTER>.

Table A2. Relevant English-to-metric conversion factors.

To convert from:	To:	Multiply by:
inches	centimeters	2.54
feet	meters	0.305
square feet	square meters	0.0929
acres	hectares	0.4046
square feet/acre	square meters/hectare	0.2296
cubic feet	cubic meters	0.02832
pounds	kilograms (1kg = 0.001 Mg)	0.4536
pounds/cubic foot	kilograms/cubic meter	16.02
pounds/square inch	pascals	6895

Figure A1. Introductory screen of CWD, version 1.4.

```
**********************************************************************
*                        CWD, version 1.4                            *
**********************************************************************

WRITTEN FOR THE TETON AND UTAH VARIANTS OF THE FOREST VEGETATION SIMULATOR

      Developed as a cooperative effort between the USFS National Fish Habitat

      Relationships Unit and the College of Natural Resources, Utah State University

                              April 27, 2000

++++++++++++++++++++++ PRESS <ENTER> TO CONTINUE +++++++++++++++++++++
```

Model Initiation Queries

Defining Stream and Forest Parameters

To begin data processing, CWD requires information about the stream, so users should have this data available before beginning the analysis. The first question refers to how long CWD simulates debris recruitment:

Enter the number of cycles for simulation (3 - 40)... >>

Users can simulate LWD delivery during the entire length of time FVS processed the inventory data, from 3 cycles (30 y) to 40 cycles (400 y), or a subset of a longer simulation run. Throughout the data query section of CWD there are limits that must be met. If these limits are violated, the user is asked to provide a suitable value. For example, CWD must run for at least 3 cycles but not more than 40 cycles; therefore, entering -10 or 5000 will result in an error message. The next question requests the afforestation of the stream reach:

Number of banks (1 or 2) CWD is recruited from ... >>

Remember that FVS tracks individual trees as representative of those found on an acre of forest, so there is a 2-dimensional component to CWD operation. In the Intermountain West, it is common to find one bank of a stream forested while the other is open. This query allows the user to adjust the simulation of a particular reach to the current conditions. More recruitment is expected from a stand with forest on both banks, and inventory procedures should include data from both sides of the channel. Entering 1 distributes the stand along one side of the bank, while a 2 places trees along both banks. The next query asks the user to:

Enter the average stream bankfull width (in feet)... >>

Bankfull width is the channel area affected by a 1 to 2 y return-interval flood (wetted width is where the water currently is, regardless of flood stage). These frequent high flows define the area that woody debris can be regularly incorporated into the stream, as substantial riparian LWD transport occurs during flood events (Bisson et al. 1987). Although a considerable amount of variability in bankfull channel width along the study reach likely exists, for predictive purposes the mean value is most appropriate. We developed CWD for streams flowing through well-defined, constrained channels. Therefore, highly braided systems should not be modeled with the current version. By default, a piece of wood is considered recruited to the riparian zone if it extends at least one meter[3] into the bankfull width zone. Once CWD is given the stream width, it prompts:

Enter the fixed forest plot width (in feet)... >>

Fixed forest plot width relates to how FVS projects stands. Since FVS operates on an areal basis, all tree parameters in the tree list file represent a sample of those located on a hypothetical acre of the stand. The fixed forest plot width demarcates the extent of sampling for the field inventory data. FVS can predict stand dynamics from different plot sizes, but moderate-sized (perhaps 0.1 ha) circular plots provide a good compromise between sampling efficiency and forest pattern. Sampling further from the channel than maximum site-potential tree height from the outer perimeter of bankfull width only surveys trees with a slight probability of entering the channel. In addition, even a few hundred feet from the channel riparian forest vegetation can differ dramatically in density and species composition, so inventory data are best gathered adjacent to the stream. CWD takes the fixed forest plot width data and uses it to standardize LWD recruitment. The results are given in volume per 100 ft (30.5 m) stream reach.

CWD subdivides the fixed forest plots into 9 zones for the purpose of determining snag spatial location. Snags can be distributed within the riparian forest zone at different densities and patterns by manipulating the number of snags within each zone. CWD defaults to a random snag location protocol, so that each of the zones have the same potential number of snags (table A3). If a different distribution is desired, simply alter the number of potential snags for each zone, keeping in mind that 9 zones are required and that the sum of all potential snags cannot exceed 50,000. CWD distributes the angle of snag fall into zones representing a progression of 20° angle classes starting at 0° (falling directly towards the channel) and ending with 180° (falling directly away from the channel). The default distribution has been fit to our field data on angle-of-fall patterns but other distributions are possible. Changing the potential number of snag-fall angles changes the distribution patterns, with the same constraints as snag locations (9 zones, not exceeding 50,000 records).

---

[3] *This distance can be altered by changing the minimum piece length (see later section on default customization).*

After the initial questions have been satisfactorily answered, CWD prompts for a confirmation of this data:

Please confirm the following riparian zone parameters:

```
======================
| Number of cycles to run  —> _____ |
| Number of forest banks   —> _____ |
| Bankfull width           —> _____ |
| Fixed forest width       —> _____ |
======================
```

Are these values correct (type 'N' to reset) (Y/N)? >>

Typing a Y accepts the data while entering N rejects all of the entered information and returns the user to the beginning of the parameterization screen.

Harvest/Disturbance Accelerated Snag Failure

Up to this point, the user has defined the physical parameters of the stream and riparian forest, but this does not affect snag behavior. The harvest and disturbance accelerated snag failure subroutine allows the user to accelerate snag failure (i.e., failure rates in excess of model defaults) that may occur with disturbance. Intended to address the impacts of timber harvesting, this subroutine can be adapted to simulate the effects of a natural catastrophic disturbance. Intense fires, for example, frequently consume much of the structural support of snags, causing them to fall at a rate exceeding unburned conditions.

A separate subroutine has been created to allow modification of other snag defaults (see *Defaults customization subroutine*), but accelerated snag failure due to disturbance was kept separate because of the instantaneous nature of these events. Accelerated failure is a cycle-specific event that affects the snags of all species in the riparian forest. With this system, the user can define multiple disturbance events of different intensities. To access the disturbance-mediated snag failure acceleration subroutine, type Y at the following prompt:

Accelerate snag failure due to
harvest or disturbance (Y/N)? >>

This option should be used when estimating riparian LWD recruitment from a FVS run that has experienced harvesting, as snags are lost from harvesting and compliance with safety regulations. New ecosystem management practices that retain some snags after harvest can still be simulated, as accelerated snag failure rates can be set for a number of different intensities. The next screen begins:

```
**********************************************************
*   HARVEST/DISTURBANCE ACCELERATED
          SNAG FAILURE SUBROUTINE              *
**********************************************************
```

You will be prompted to enter the cycle in which the event occurs and the intensity of the event. Note that the cycle number cannot exceed the number used by FVS, and that the intensity of the disturbance is bounded between 0 and 100.

Cycle of disturbance event
(press only <ENTER> when done) >>

The disturbance is called an event, the cycle number cannot exceed the number of cycles possible (as indicated by the simulation period), and disturbances events cannot have intensities < 0 or > 100 (the higher the number, the more strongly the event accelerates snag failure). Note the cycle of the disturbance event should be noted by the user before beginning CWD to ensure coordination between the event and the accelerated snag failure. If multiple events are used, enter them in any order, and correct errors simply by reentering the cycle and event intensity. Once CWD has the cycle of the event, it asks for:

Intensity of disturbance event (0 - 100) >>

CWD then confirms the information entered by displaying:

Disturbance event of intensity ___ recorded in cycle ___
Proceeding to the next event...

The blanks represent the new data entered. After this information is gathered, the user can either add additional disturbance events by typing the cycle of the event or exit back into the main program by pressing <ENTER> at the prompt. Disturbance accelerated snag failure is possible at every, only one, or no cycles.

File Management System

The next section of CWD concerns the file management processes needed for successful operation. The first prompt:

Enter file name containing the FVS treelist data... >>

queries the user to enter the file name where the FVS projected tree list data are contained. This file can be located in a subdirectory different from the one in which CWD is located as long as the full path is provided. The user is then asked for names of the primary output files CWD generates:

Enter file name for CWD.EXE demographic results... >>

Enter file name for CWD.EXE summary results... >>

CWD creates each file as if new, so *make sure that files get unique names or CWD will overwrite them.* The demographics file contains information on the probability of piece recruitment based on piece size, while the summary file provides a list of reach-related LWD attributes by cycle. Both of these files are discussed in detail later in this appendix. After CWD is instructed where to place the output information, it creates each file and displays the following message:

Capturing CWD.EXE default settings...

At this point, CWD readings the DEFAULT1.CWD file from the same subdirectory in which CWD is located. DEFAULT1.CWD is an ASCII file that contains many of the default settings for CWD (table A3). The program displays an error message if it cannot find DEFAULT1.CWD and operation ceases. *Do not rename* DEFAULT1.CWD, and make sure it is in the correct subdirectory. These defaults can be edited, but keep in mind that some functions within CWD are strictly bounded so adjustments may not have the desired effect.

Default Customization Subroutine

The user is allowed to customize within bounds many of the defaults used by CWD to fit local conditions. After the file management section of CWD has finished, the following question appears:

Would you like to customize CWD.EXE defaults (Y/N)? >>

A negative response immediately begins CWD processing with model defaults, while a positive response initiates the following screen:

```
*******************************************************************
*   CWD.EXE DEFAULTS CUSTOMIZATION
              SUBROUTINE                                          *
*******************************************************************
```

You will be prompted to adjust the simple functions used to calculate the default environmental modifiers. Please consult the manual if you have any detailed questions on how the modifiers work. Press <ENTER> at any prompt to retain the default value and skip to the next section.

Consult table A3 for existing default values. When annotating CWD model defaults, pressing <ENTER> allows you to skip to the next subsection. If an error is made while entering the data and <ENTER> is pressed, continue pressing <ENTER> to move to the end of the default modification section and repeat the customization routines. The first defaults that are customized are the snag failure modifiers. As mentioned, several factors are used to predict snag longevity: species, diameter, and time since death. Harvest, which also accelerates snag failure, has already addressed. Each factor is formulated with the following response function:

$$Y = a + bX^c \quad \text{(A1)}$$

Table A3. Data contained in DEFAULT1.CWD.

5555	5555	5555	5555	5555	5555	5555	5555	5555	(snag distribution)
8900	3900	3900	3900	8800	3900	3900	3900	8900	(AOF distribution)
0.000000									(ASPPMOD)
1.000000									(BSPPMOD)
1.000000									(CSPPMOD)
17.000000									(ADBHMOD)
-0.333333									(BDBHMOD)
1.000000									(CDBHMOD)
6.000000									(ATIMEMOD)
3.000000									(BTIMEMOD)
1.200000									(CTIMEMOD)
10.000000									(ASNGBRK)
15.000000									(BSNGBRK)
2.000000									(CSNGBRK)
33.333333									(FAIL_NUM)

where magnitude of the predicted response (Y) is a function of the factor and 3 coefficients (a, b, and c). The minimum value of every function is zero and the maximum = 100. This simple equation can generate a number of different patterns (figure A2), so examine modifications to model behavior before adjusting the modifiers. Species modifiers are based on modulus of rupture data gathered from Panshin and deZeeuw (1980). Species are aggregated into 1 of 7 classes (table A4), but the species modifier has only a slight impact on snag behavior. The other modifiers vary continuously with size, time since snag creation, and harvest intensity. All modifiers are summed together, and this grand total cannot be less than zero nor exceed 100. This sum is converted to a ratio with a value between 0 and 1, multiplied by a random number (also between 0 and 1). The sum is then compared to a threshold fail value (FAIL_NUM in table A3). If the threshold fail number is greater than the computed modifier total, the snag is transferred to the failure pool for stream recruitment. Otherwise, it is assumed that it "survived" into the next cycle, although pieces may be fragmented off the standing snag.

Snag fragmentation occurs to all snags to varying degrees depending on how long they have been standing. More pieces will break off and potentially become LWD themselves the longer a snag remains standing. As with the snag residency modifiers, snag fragmentation follows equation [A1] where X becomes snag residency. Pieces that fragment off of standing snags are randomly sized, but

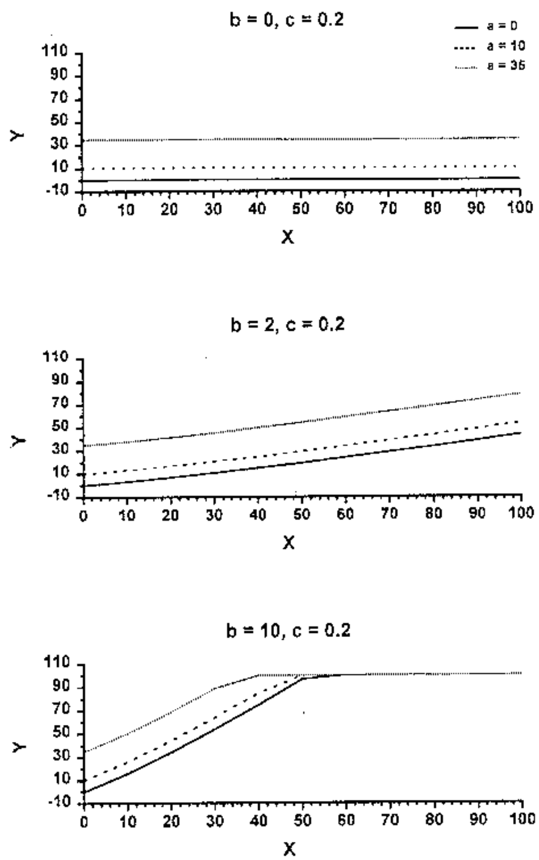

Figure A2. Possible outcomes of equation A1 ($Y = a + bX^c$) using different values for *a*, *b*, and *c*.

Table A4. Species-based modulus of rupture (MOR) classes used by CWD.

MOR class[a]	Modifier class (SPP_MOD)	Species
11,000 +	1	
8,000 - 11,000	2	
7,000 - 8,000	3	Douglas-fir
6,000 - 7,000	4	Limber pine, *Populus*, lodgepole pine, Engelmann spruce, blue spruce, subalpine fir
5,000 - 6,000	5	
4,000 - 5,000	6	
< 4,000	7	

[a] MOR in pounds per square inch. Values are adapted from Panshin and deZeeuw (1980).

they increase in size as snag residency increases so that young snags may lose only a small portion of their length but old snags could lose most of it. This concludes the capacity the user has to modify snag dynamics. The next customization section deals with LWD pattern and process:

Default minimum diameter for inclusion as CWD = 4 in.

New minimum diameter threshold...? >>

Since there is no standard definition of LWD (either piece diameter or length), CWD was designed to allow the user to determine what size pieces qualify. Minimum piece diameter is the minimum small-end diameter and must be > 0 but less than 360 inches (915 cm) (CWD defaults to 4 inches (10 cm)). This diameter also defines the smallest recruited pieces reported in the output tables generated by CWD. Although the user is granted considerable latitude in determining minimum diameter and length, the largest tree in the world has a diameter of ~ 320 inches (~ 812 cm). Also note that there is not a maximum diameter or length for inclusion as LWD. CWD assumes that once the minimum thresholds are surpassed, the piece qualifies. After the minimum diameter threshold has been set, the next option appears:

Default minimum length for inclusion as CWD = 3 ft.

New minimum length threshold...? >>

Piece length is the most critical dimension of LWD as it is most directly related to retention within the channel. There is little difference in retention time from a piece that is 4 inches (10 cm) from one that is 8 inches (20 cm) in diameter, but there is a major difference for a piece that is 6 ft (1.8 m) versus one that is 12 ft (3.7 m) long. CWD assumes pieces are at least 3 ft (1 m) long. The user is allowed to customize minimum piece length so that it ranges from 1 to 400 ft (0.3 to 122 m). Again, user discretion is advised in setting minimum piece length.

Because CWD lacks the exact spatial and temporal location of each fallen snag, predicting how they fragment is complicated. Rather than estimating fragmentation over time while the piece lays on the ground, the snag is assumed broken as possible the instant it falls. To estimate how many pieces are formed, a field survey of fallen snags was taken (figure A3) in which the number of pieces were tallied. CWD assumes the snag breaks randomly along the bole, and that the likelihood of a certain number of breaks (e.g., none, 1, 2, 3, ...) fits a probability distribution. CWD's default probability distribution was designed to fit the piece length distribution noted in Dry Lake Creek, but the user has the flexibility to reset this distribution to fit their region:

Maximum POSSIBLE number of breaks for fallen snags = 20

CURRENT maximum number of breaks for fallen snags = 12

New maximum number of breaks...? >>

While the maximum possible number of breaks (20) in CWD and the default maximum number of breaks (12) may seem high, the distribution achieved by the default distribution used by CWD makes it very unlikely that 12 breaks per snag will occur. Although this fits central Rocky Mountain spruce-fir forests well, it may not be appropriate for other cover types. If a new maximum number of breaks is selected (0 to 20), then the user is prompted to enter the break sensitivity thresholds:

Default thresholds for number of breaks =

...CWD then lists the default thresholds for up to 12 breaks...

Threshold 1 ...is ALWAYS zero...

Threshold 2 = 0.06

New threshold...? >>

This process continues until all new thresholds are defined. Users can still use 12 breaks as the default by simply changing the individual thresholds for a different pattern. Keep in mind that the propensity of a snag to fragment is a product of how long the snag remains standing and its height (more breaks occur in old, tall snags). A random component is also factored in so that snag break thresholds are

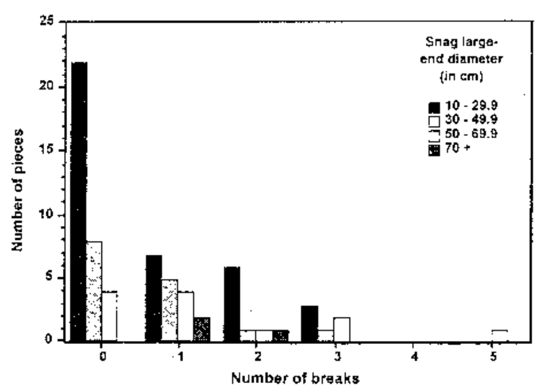

Figure A3. Field samples by snag size, collected to determine the likelihood of snag fragmentation when it is on the ground.

most effective when they are fractionally small and they have less impact as they increase. Because determining an effective break threshold distribution is difficult, we caution against changing the defaults.

A new component of version 1.4 is a slope factor used to determine piece recruitment. Earlier versions of CWD assumed that the riparian forest covered a flat surface at the same elevation as the stream channel. Since many forested streams flow through steep, confined drainages, we included the capacity to address slope effects on LWD recruitment:

Default elevation at the furthest edge of the forest plot = 0

New elevation...? >>

Elevation is the height of the furthest edge of the forest plot (see earlier definition) above the channel (not sea level). While relatively crude, it adds a vertical dimension to piece recruitment. Steep slopes limit recruitment by lengthening the amount of bank a piece has to cover before it enters the channel (figure A4). Plot edge elevation must be between 0 and 400 ft (0 to 122 m).

The user can also select the number and dimensions of the size classes used in the CWD demographics output file. The first option is to alter the number of large-end diameter classes:

Default number of CWD large-end diameter classes = 10

New number of CWD diameter classes...? >>

Up to 20 diameter classes are allowed (minimum number = 1). After the number of classes has been selected, the range of each class can be defined. CWD first lists the 10 default diameter classes:

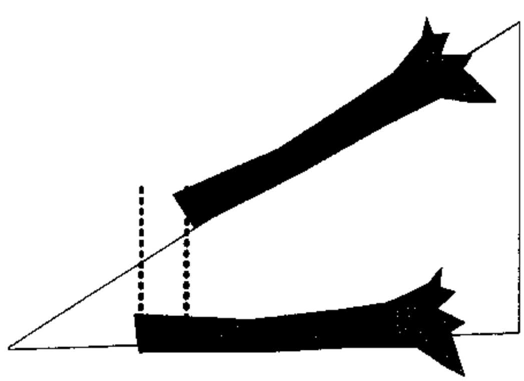

Figure A4. CWD slope effect on piece recruitment. CWD assumes slope reduce recruitments by forcing a piece of large woody debris to cover more distance to reach the stream (dashed lines).

Default diameter thresholds for CWD diameter classes:

DIAMETER CLASS 1 = 6 TO 7.99 INCHES

DIAMETER CLASS 2 = 8 TO 9.99 INCHES

DIAMETER CLASS 10 = 60 TO 360.00 INCHES

New default diameter thresholds
(minimum diameter has already been set)...?

Diameter class: 1 >>

If the user has redefined minimum piece diameter, it becomes the new minimum diameter for the demographics output file. Maximum piece diameter is constrained at 360 inches (915 cm) (see earlier maximum diameters discussion). Each progressive diameter class must be larger than the previous one, but it is unnecessary for all diameter classes to be proportionally wide. This allows variable-sized diameter classes. A similar strategy is used for length classes:

Default number of riparian CWD length classes = 10

New number of riparian
CWD length classes...? >>

There can be anywhere from 1 to 20 length classes. As with the diameter classes, CWD provides a list of the 10 default length classes:

Default length thresholds for riparian CWD length classes:

LENGTH CLASS 1 = 6 TO 9.99 FEET

LENGTH CLASS 2 = 10 TO 14.99 FEET

LENGTH CLASS 10 = 100 TO 400.00 FEET

New default length thresholds
(minimum length has already been set)...?

Length class: 1 >>

The user can reset the number of internal self-replicates that CWD will automatically process:

Current number of model self-replicates = 1

New number of model self-replicates...? >>

A self-replicate is one loop through the entire CWD process for a simulation run. Because of the stochastic nature of some CWD subroutines, there can be considerable variance in debris production from one run to the next. Thus, to provide a better estimate of mean recruitment, CWD automatically runs 5 self-replicates. However, if the user is interested in portraying some of the variance in recruitment, the number of self-replicates can be changed (to a range of 1 to 5 per run).

The last stage of the CWD default customization subroutine is a series of review screens to confirm the modified. After the number of self-replicates has been determined, the following prompt appears:

===> Press <ENTER> to see the new default settings...

After the enter key is pressed, modified default settings appear (this example uses CWD defaults):

SPPMOD: A = 0.000000 B = 1.000000 C = 1.000000

DBHMOD: A = 17.000000 B = -0.333333 C = 1.000000

TIMEMOD: A = 6.000000 B = 3.000000 C = 1.200000

SNGBRK: A = 10.000000 B = 15.000000 C = 2.000000

MINDIA = 4.00

MINLEN = 3.00

MAXBREAK = 12

BREAK THRESHOLDS = 0.00 0.06 0.12 0.24 0.48 0.96 1.92

BREAK THRESHOLDS = 3.84 7.68 15.36 30.72 100.00

BREAK THRESHOLDS =

MAXIMUM EDGE OF FOREST PLOT ELEVATION = 0.0

SELF-REPLICATES = 5

===> Press <ENTER> to continue viewing new default settings...

...next screen...

NUMBER OF DIAMETER CLASSES = 10

DIAMETER CLASS 1 = 4 TO 6 INCHES

DIAMETER CLASS 2 = 6 TO 8 INCHES

DIAMETER CLASS 3 = 8 TO 10 INCHES

DIAMETER CLASS 4 = 10 TO 15 INCHES

DIAMETER CLASS 5 = 15 TO 20 INCHES

DIAMETER CLASS 6 = 20 TO 30 INCHES

DIAMETER CLASS 7 = 30 TO 40 INCHES

DIAMETER CLASS 8 = 40 TO 50 INCHES

DIAMETER CLASS 9 = 50 TO 60 INCHES

DIAMETER CLASS 10 = 60 TO 360 INCHES

===> Press <ENTER> to continue viewing new default settings...

...next screen...

NUMBER OF LENGTH CLASSES = 10

LENGTH CLASS 1 = 3 TO 6 FEET

LENGTH CLASS 2 = 6 TO 10 FEET

LENGTH CLASS 3 = 10 TO 15 FEET

LENGTH CLASS 4 = 15 TO 20 FEET

LENGTH CLASS 5 = 20 TO 30 FEET

LENGTH CLASS 6 = 30 TO 40 FEET

LENGTH CLASS 7 = 40 TO 60 FEET

LENGTH CLASS 8 = 60 TO 80 FEET

LENGTH CLASS 9 = 80 TO 100 FEET

LENGTH CLASS 10 = 100 TO 400 FEET

Are these values correct (type 'N' to reset) (Y/N)? >>

To change one of the values listed, answer N to return to the initial customization stage. This requires going through the default customization subroutine again. If new default values are acceptable, enter Y at the prompt to begin model processing:

****

*** USE <CTRL> + <BREAK> TO INTERRUPT MODEL AT ANY TIME ***

****

Reading input treelist file data...

Locating snags...

Determining snag residency...

Determining angle of snag fall...

Fragmenting fallen snags...

Writing to P_CWD.OUT file...

...then 4 more layers of these screen registers...

Recapturing P_CWD.OUT

Opening CWDIN.OUT

Determining which pieces enter the stream...

Creating CWD.EXE output files...

CWD.EXE PROGRAM FINISHED!!

The first group of comments indicates stages that CWD passes through as it manipulates snags. The second group indicates the treatments being performed and other file management processes.

Output Files Created by CWD

CWD generates a series of ASCII output files during its processing, each of which can be used for model adjustment or recruitment analysis. These files are:

- DEAD.OUT
- BRK_DIST.OUT
- P_CWD.OUT
- CWDIN.OUT
- demographics file (user-provided file name)
- summary file (user-provided file name)

DEAD.OUT is a list of the snags extracted from the FVS tree list file that provide the basis for all CWD analysis. BRK_DIST.OUT is a file that lists the number of snag break distributions generated by CWD. The snags are only fragmented when they fall, so accurate piece size distributions are vital for further analysis. BRK_DIST.OUT can be used to calibrate break point distribution patterns to fit the desired pattern. This file contains 3 columns: snag number (SNAG#), snag residency (RES), and number of breaks (#BRK). These data can be aggregated into snag residency or number of snag break distributions.

The next file generated (P_CWD.OUT) contains information on pieces with the *potential* to enter the bankfull width channel zone, including: piece number (PIECE#), species (SPP), large-end piece diameter (D_BOT), small-end piece diameter (D_TOP), piece length (LEN), distance from bankfull channel edge (XLOC), angle of snag fall (AOF), cycle of snag fall (CYCLE), and self-replicate number (SERP). The only way debris enters this file is if it meets the minimum length and small-end diameter criteria.

After passing through a final filter which determines the debris actually recruited to the bankfull width zone, CWD writes a file with the properties of all pieces (CWDIN.OUT), including piece number (PIECE NUMBER), FVS species code (SPP CODE), bottom-end piece diameter (BOT. DIA.), top-end piece diameter (TOP DIA.), LWD piece length (PIECE LENGTH), location of piece relative to the bankfull channel (PLANE X LOC.), direction of LWD piece fall (PIECE AOF), cycle the piece was generated (CYC), and self-replicate number (SRP).

These intermediate files always have the same content and file name. To keep a specific run of these files, it is necessary to rename the files after that run is complete. The demographic and summary files, conversely, are named by the user when the run is initiated, and unique file names should be created at that time.

Demographic and Summary Files

The files most critical to analysis of LWD recruitment are the demographic and summary files. The demographic file summarizes the riparian piece recruitment patterns expected for all self-replicates, standardized per 100 ft (30.5 m) reach of stream channel. This file (figure A5) begins by listing the FVS tree list and demographic file names for this particular run, followed by the user-defined (or default) diameter and length class definitions (listed because only codes of size class are provided in the following tables). The number of pieces delivered per 100 ft (30.5 m) reach is then provided, which can be fractional due to how CWD operates. First, remember that CWD uses a stand expansion factor to boost mortality sensitivity. This expansion factor translates into mortality per unit area because FVS tracks individual tree records as representative over an acre, so each record usually represents multiple trees. Therefore, as the contributing stand is defined and recalibrated to fit the standard stream reach used in CWD, fractions of pieces are generated. Second, both the demographics and summary output files are averages of multiple self-replicates. The stochastic routines in CWD generate different recruitment during each self-replicate so when the average is calculated fractions can occur.

Most of the demographics file is a table of recruitment probabilities by diameter and length class generated for every cycle. Probability of recruitment (to 3 decimal places) is calculated by dividing the number of pieces CWD recognizes as delivered to each size class by the total number of pieces recruited in that cycle. Probabilities are difficult to interpret, but they indicate the recruitment patterns experienced in each cycle. For example, figure A5 displays the demographics of the first cycle in a demographics file in which most pieces recruited to the channel are small. Occasionally, larger pieces appear, but these are relatively infrequent (probabilities ~ 0.009).

The summary file contains the predictions generated by CWD (figure A6). The data are a summary of the recruitment patterns by each 10 y cycle for a standard 100 ft (30.5 m) reach of the subject stream. Mean diameter averages large-end piece diameter, while mean length represents the average piece length. Both of these values can be used to help evaluate CWD's performance to that experienced in the field. The final columns provide estimates of LWD volume recruited to the channel by cycle. If the user prefers recruitment as biomass rather than volume, we recommend consulting Harmon et al. (1986) for appropriate conversion factors.

Troubleshooting

We realize this is not a comprehensive list of potential problems, and we welcome comments on errors, interpretation difficulties, or source code bugs. Contact D.C. Bragg to report problems.

Use of the Metric System

CWD is designed to operate with English units because FVS uses the English system. Keep this in mind when field sampling, running FVS and CWD, interpreting CWD output, and especially when customizing CWD operation. Using centimeters or meters rather than inches or feet could cause CWD to function improperly or to generate illogical results (table A2 converts English to metric units).

Illegal File Names or Missing Data Files

CWD requires that DEFAULT1.CWD exists in the same subdirectory as the executable CWD.EXE and that its formatting matches CWD's expectations (see table A3). FVS tree list file can be in any path that DOS can recognize, but it also needs to follow the formatting expected by CWD. Deviation from required patterns can lead to either error messages or incorrect analysis. Any file name and extension acceptable for DOS can be used to label the demographics and summary files, but it is up to the user to ensure that unique file names are given to avoid over-writing old data files.

```
CWD VERSION USED TO MAKE THIS FILE:            1.4
DATE AND TIME THIS FILE WAS CREATED:           10/15/98   13:51:36
FVS TREELIST FILE NAME:                        NOTMT1.LST
PIECE DEMOGRAPHICS FILE NAME:                  RUN1_1.DEM
====================================================

DIAMETER CLASS DEFINITIONS:
D_CLASS   1   RANGES FROM    4.0  INCHES TO    6.0  INCHES
D_CLASS   2   RANGES FROM    6.0  INCHES TO    8.0  INCHES
D_CLASS   3   RANGES FROM    8.0  INCHES TO   10.0  INCHES
D_CLASS   4   RANGES FROM   10.0  INCHES TO   15.0  INCHES
D_CLASS   5   RANGES FROM   15.0  INCHES TO   20.0  INCHES
D_CLASS   6   RANGES FROM   20.0  INCHES TO   30.0  INCHES
D_CLASS   7   RANGES FROM   30.0  INCHES TO   40.0  INCHES
D_CLASS   8   RANGES FROM   40.0  INCHES TO   50.0  INCHES
D_CLASS   9   RANGES FROM   50.0  INCHES TO   60.0  INCHES
D_CLASS  10   RANGES FROM   60.0  INCHES TO  360.0  INCHES

LENGTH CLASS DEFINITIONS:
L_CLASS   1   RANGES FROM    3.0  FEET TO      6.0  FEET
L_CLASS   2   RANGES FROM    6.0  FEET TO     10.0  FEET
L_CLASS   3   RANGES FROM   10.0  FEET TO     15.0  FEET
L_CLASS   4   RANGES FROM   15.0  FEET TO     20.0  FEET
L_CLASS   5   RANGES FROM   20.0  FEET TO     30.0  FEET
L_CLASS   6   RANGES FROM   30.0  FEET TO     40.0  FEET
L_CLASS   7   RANGES FROM   40.0  FEET TO     60.0  FEET
L_CLASS   8   RANGES FROM   60.0  FEET TO     80.0  FEET
L_CLASS   9   RANGES FROM   80.0  FEET TO    100.0  FEET
L_CLASS  10   RANGES FROM  100.0  FEET TO    400.0  FEET
====================================================
PIECES DELIVERED PER 100 ft (30.5 m) STREAM REACH (THIS CYCLE):   1.446

PROBABILITY OF RECRUITMENT WITHIN A GIVEN CLASS:
                     LENGTH CLASS
CYCLE   DCLS      1     2     3     4     5     6     7     8     9    10
  1       1    .116  .089  .027  .000  .009  .000  .000  .000  .000  .000
  1       2    .045  .054  .054  .027  .000  .000  .000  .000  .000  .000
  1       3    .018  .045  .063  .080  .036  .000  .000  .000  .000  .000
  1       4    .089  .045  .071  .027  .018  .018  .000  .000  .000  .000
  1       5    .000  .018  .009  .000  .000  .009  .009  .000  .000  .000
  1       6    .000  .000  .000  .000  .000  .009  .000  .000  .000  .000
  1       7    .000  .000  .009  .000  .000  .009  .000  .000  .000  .000
  1       8    .000  .000  .000  .000  .000  .000  .000  .000  .000  .000
  1       9    .000  .000  .000  .000  .000  .000  .000  .000  .000  .000
  1      10    .000  .000  .000  .000  .000  .000  .000  .000  .000  .000
```

Figure A5. Example CWD demographics output file.

Input Fle Too Large or Too Many Pieces of CWD Generated

An error may arise if the input tree list file is too large. CWD can only read a file with ≤50,000 tree records, which should be plenty for one-acre plots covered with LWD-sized trees for 40 cycles. However, it is possible to exceed this number if dense regeneration is included in the FVS tree list file. If this is the case, eliminate saplings until there are ≤ 50,000 records. CWD can only manage 250,000 pieces of debris, if this array size is exceeded adjust FVS so it creates fewer pieces.

Exceeding Reasonable Value Limits

It is possible to exceed parameter value limits. While most of the code of CWD has been written to avoid unreasonable customization, careless alteration of defaults can lead to nonsensical relationships between parameters and therefore generate unrealistic values. While we believe the customization capacity of CWD adds strength and flexibility to its performance, this ability can be a double-edged sword. Check the relationships between parameters and how they react to customization before attempting significant adjustments.

CWD VERSION USED TO MAKE THIS FILE: 1.4
DATE AND TIME THIS FILE WAS CREATED: 10/15/98 13:51:36
FVS TREELIST FILE NAME: NOTMT1.LST
RIPARIAN CWD SUMMARY FILE NAME: RUN1_1.SUM

RIPARIAN CWD SUMMARY PER 100 ft (30.5 m) STREAM REACH BY CYCLE

CYCLE	NEW PIECES (#)	MEAN DIA. (in)	MEAN DIA. (cm)	MEAN LENGTH (ft)	MEAN LENGTH (m)	CWD VOLUME (ft3)	CWD VOLUME (m3)
1	1.45	9.40	23.89	11.66	3.56	10.65	.30
2	8.62	9.09	23.10	9.81	2.99	47.61	1.35
3	8.44	9.43	23.95	10.34	3.15	50.20	1.42
4	9.44	9.82	24.95	9.61	2.93	54.79	1.55
5	6.66	10.60	26.94	9.84	3.00	42.06	1.19
6	5.83	10.09	25.62	10.35	3.16	38.80	1.10
7	5.79	10.66	27.09	9.12	2.78	34.45	.98
8	4.40	10.54	26.78	10.34	3.15	31.17	.88
9	4.74	10.49	26.63	10.57	3.22	33.36	.94
10	7.03	11.58	29.42	9.50	2.90	52.46	1.49
11	4.76	11.00	27.93	9.06	2.76	31.68	.90
12	3.15	10.58	26.88	10.04	3.06	20.95	.59
13	4.75	10.61	26.94	9.22	2.81	33.59	.95
14	2.88	11.08	28.14	9.89	3.02	21.95	.62
15	3.52	10.58	26.88	9.74	2.97	26.40	.75
16	5.78	11.08	28.15	8.79	2.68	40.88	1.16
17	3.19	9.66	24.53	8.21	2.50	17.02	.48
18	3.19	9.64	24.48	9.28	2.83	19.26	.55
19	4.92	10.79	27.42	8.22	2.51	28.81	.82
20	3.32	10.15	25.78	9.09	2.77	23.42	.66
21	2.83	11.18	28.41	9.92	3.03	26.48	.75
22	3.96	10.77	27.35	7.75	2.36	21.95	.62
23	3.85	10.88	27.63	8.93	2.72	29.02	.82
24	3.47	11.19	28.43	10.88	3.32	32.19	.91
25	3.42	11.26	28.60	10.61	3.24	29.43	.83
26	3.03	9.74	24.73	9.36	2.85	22.60	.64
27	2.60	10.24	26.02	9.20	2.81	18.70	.53
28	3.47	10.66	27.08	8.74	2.66	20.91	.59
29	3.17	11.64	29.57	10.39	3.17	30.73	.87
30	2.84	11.31	28.72	9.26	2.82	22.14	.63

Figure A6. Example CWD summary output file.

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