An Individual Tree Simulation Model for Estimating Expected Values of Potentially Available Large Woody Debris (LWD) (DRAFT)

Kevin R. Gehringer, Ph.D. *

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Abstract

An individual tree based simulation model for estimating expected values of potentially available large woody debris (LWD) was developed. Potentially available LWD was defined as LWD that could be recruited into a stream, from the standing live trees in an adjacent forest, if the trees were to fall. Expected values were based on stream intersection probabilities for the standing live trees, a distribution of tree fall directions, a model for computing the dimensions of a potential stream intersecting log that could produce an LWD log, and minimum dimensions for LWD logs and functional LWD logs.

The LWD simulation model was used to estimate expected values for potentially available functional LWD for riparian forests in western Washington (USA) using data from 179 sample plots. The dimensions of LWD that function within a stream channel, providing bank stability or forming pools, were assumed to vary with stream size: larger streams require larger functional LWD logs than smaller streams. Potentially available functional LWD was estimated using different minimum LWD log dimensions to identify functional logs for six stream size classes having bank-full widths in the range from 3.3 ft to 75.5 ft. Expected values were computed for potentially available functional LWD volume ($ft^3 ac^{-1}$) and number of pieces ($n\ ac^{-1}$) for a 170 ft wide, one acre buffer on one side of a stream. Stream intersection probabilities were assumed to be based on a uniform probability of tree fall direction, trees within a forest stand adjacent to a stream were assumed to be uniformly distributed, and all trees were

*6215 225th Ave. NE, Redmond, WA, 98053

assumed to fall perpendicular to their adjacent stream to simplify the LWD log size and volume computations.

Mean expected values of potentially available functional LWD volume (pieces) ranging from 801.0 ft^3ac^{-1} (2.1 pieces ac^{-1}) for the largest stream class to a maximum value of 1580.4 ft^3ac^{-1} (17.6 pieces ac^{-1}) for the smallest stream class were predicted by the model. The model also predicted that approximately 50% of the potentially available functional LWD volume (pieces) would occur within 11.5 ± 7.6 ft (14.3 ± 12.0 ft) of the stream for the largest stream class and within approximately 24.0 ± 4.2 ft (34.4 ± 9.3 ft) of the stream for the smallest stream class. Approximately 90% of the potentially available functional LWD volume (pieces) was predicted to occur within 42.9 ± 21.5 ft (49.6 ± 28.3 ft) of the stream for the largest stream class and within 69.6 ± 11.1 ft (93.6 ± 18.5 ft) of the stream for the smallest stream class.

1 Introduction

An understanding of the roles played by forests that are adjacent to streams has become an important component of forest management in the Pacific Northwest and in Washington State (FFR, 1999, Ehlert and Mader, 2000, Fairweather, 2001). These roles include, but are not limited to, bank stability, shade production, habitat for wildlife, and the production of large woody debris (LWD). The presence of LWD in a stream influences the channel morphology, the frequency, size, and structure of pools, the rates and locations of sediment deposition, as well as providing suitable habitat for fish (Bilby and Ward, 1989, McDade et al., 1990, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Welty et al., 2002). The ability of a forest adjacent to a stream to produce LWD that may be recruited into the stream channel over time has become of particular importance (FFR, 1999).

Given the importance of instream LWD to stream function, and its role in the creation of potential fish habitat, a number of models have been developed to estimate the expected LWD contribution to a stream from the adjacent forest stand or some of its characteristics (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Cross, 2002, Welty et al., 2002). The models may be divided into two general types: LWD recruitment models (Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) and LWD availability models (Robison and Beschta, 1990, Cross, 2002).

LWD recruitment models estimate the expected amount of LWD that *has potentially been recruited* into a stream channel from the adjacent forest (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002). The objective of an LWD recruitment model is, therefore, to identify the potential amount of LWD that is likely to actually enter a stream from trees that fall in the adjacent forest at any point in time, or the recruitment rate (Robison and Beschta, 1990, Van Sickle and Gregory, 1990). The recruitment rate may then be integrated over time to obtain an estimate of the amount of

LWD that was potentially recruited into a stream channel from the adjacent forest over a period of time (Beechie et al., 2000, Welty et al., 2002).

LWD availability models estimate the expected amount of LWD that *could potentially be available for recruitment* into a stream channel from the adjacent forest (Robison and Beschta, 1990, Cross, 2002). The objective of an LWD availability model is, therefore, to identify the potential amount of LWD that is likely to be available to enter a stream at the current time based on the standing live trees in the adjacent forest. Dead trees or trees that have already fallen have either contributed to instream LWD or not by the current time, but they do not influence the potential amount of LWD that is available from the standing, live trees in a forest adjacent to a stream.

LWD recruitment models and LWD availability models are closely related. When LWD is actually recruited into a stream channel from the adjacent forest, the LWD must come from the pool of potentially available LWD in that forest: standing live or recently dead trees that fell and intersected the stream. Therefore, given sufficiently good estimates of LWD recruitment rates, estimates from an LWD availability model could be used to estimate LWD recruitment into a stream channel. LWD recruitment models and LWD availability models are essentially opposite sides of the same coin, with LWD recruitment models being past-looking and cumulative, while LWD availability models are future-looking and instantaneous.

Three factors directly affect the production of instream LWD, and, hence, models that are developed to estimate it: 1) the probability of tree fall and stream intersection, 2) the distribution of tree sizes within a riparian area, and 3) the locations of the individual trees in a riparian area relative to a stream. A fourth factor, whether the model aggregates based on area or trees, is also important, and affects the resolution that may be obtainable. We discuss each of these factors in turn, giving a brief description of how they have been represented in the LWD recruitment and availability models, highlighting some of their potential limitations. Finally, a need for greater detail and flexibility in LWD models is identified, and a simulation based alternative is proposed as a framework for model development and use that may provide the increased level of detail and flexibility that are necessary.

1.1 Tree fall and stream intersection

The determination of the probability of a tree falling and intersecting a stream so that a piece of LWD is produced is, possibly, the most fundamental component of any LWD recruitment or availability model. A number of factors may affect the probability of a tree falling and intersecting a stream to produce LWD including, but not limited to, the distance of a tree from a stream, the height of a tree, the taper of a tree or its diameter, the slope, the wind direction and speed, bank erosion, mortality rates, soil characteristics, and edge effects (McDade et al., 1990, Van Sickle and Gregory, 1990, Welty et al., 2002). These factors are not necessarily independent of one another, and they may interact in a complex manner.

LWD recruitment models have typically attempted to model the tree fall and stream intersection probabilities directly. They have assumed the existence of a tree fall rate, and then combined this rate with a probability of stream intersection model to obtain estimated values for potential instream LWD (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002). Large uncertainties, however, are present in the rates of tree fall for riparian forests, given the many possible physical causes, (Beechie et al., 2000, Welty et al., 2002). LWD recruitment models have typically assumed that tree fall rates were directly related to stand mortality and independent of the probability of stream intersection, (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002), while recognizing that mortality was only one possible cause of tree fall. Given the large uncertainties that exist for tree fall rates and the reliance on stand mortality, their inclusion in LWD recruitment models may not adequately represent the LWD recruitment processes.

LWD availability models use only a probability of stream intersection model to estimate the LWD that could potentially be available for recruitment into a stream (Robison and Beschta, 1990, Cross, 2002). The LWD availability model, therefore, does not require the assumption of a tree fall rate, while automatically accounting for mortality, since only standing live trees at a particular point in time may potentially contribute to available LWD. An LWD availability model may, then, provide a simpler model, possibly having a lower level of uncertainty.

The probability of stream intersection has been modeled similarly for both LWD recruitment and availability models. Probabilities of stream intersection have been assumed to depend on a distribution of tree fall directions, the size (height) of a tree, and its distance from a stream (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Cross, 2002). The physical geometry of the tree location relative to the stream and the tree size have been used to identify a range of tree fall directions that would result in a stream intersection, independent of other factors, for a tree if it fell or was to fall. The range of stream intersecting tree fall directions has then been used with the distribution of tree fall directions to compute a probability of stream intersection. A uniform distribution of tree fall directions has typically been assumed (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Cross, 2002), but is not necessary. Van Sickle and Gregory (1990) have provided a more general formulation of the problem that would allow empirically determined tree fall direction distributions to be used.

1.2 Tree size distribution

Tree size is another factor affecting the production of instream LWD: larger trees may produce larger pieces of LWD, depending on their distance from a stream. This is particularly relevant for the production of functional LWD, for which the number of LWD pieces and the size of LWD logs varies by stream size (Bilby and Ward, 1989, 1991, Beechie and Sibley, 1997, Beechie et al., 2000, Welty et al., 2002). The frequency of LWD logs providing for stream functions, e.g., pool creation, is lower for larger streams than for smaller streams, and the dimensions of the functional LWD logs are also larger for the larger streams (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Welty et al., 2002). Assumptions relating to the distribution of tree sizes in forested riparian areas, then, directly affects the potential amount of potential LWD estimated using a recruitment or availability model.

LWD recruitment models and LWD availability models both require some assumptions about the distributions of tree sizes. Since tree height has the most influence on the production of LWD, through the stream intersection probability, the size distributions have most frequently been stated in terms of height distributions. Tree heights have been assumed to equal for all trees (McDade et al., 1990, Cross, 2002), or to be uniformly distributed through one or more ranges (Van Sickle and Gregory, 1990). Tree size distributions assumptions have also been for tree diameters (Robison and Beschta, 1990). These assumptions were made to simplify the computations necessary to derive formulas that were used to estimate potential LWD for a riparian area. The assumption of a uniform distribution for tree size, or a mixture of uniform distributions, may not reflect the variability of actual tree size distributions that could occur, which could be bell shaped or even multimodal. The assumption of a uniform distribution of tree heights may, therefore, be too restrictive. An LWD availability or recruitment model having no height, or tree size, distribution restrictions would be preferable, and should be feasible to produce.

1.3 Tree location relative to a stream

The location of a tree relative to a stream, given by its perpendicular distance from the stream, also significantly affects the production of instream LWD: large trees may produce large pieces of LWD if they are close to the stream, or they may produce no LWD or small pieces of LWDif they are located far from the stream. Again, this is particularly relevant for the production of functional LWD for which the number of LWD pieces and the size of LWD logs varies by stream size (Bilby and Ward, 1989, 1991, Beechie and Sibley, 1997, Beechie et al., 2000, Welty et al., 2002).

LWD recruitment models and LWD availability models both require assumptions about the distribution of tree distances from a stream. This distribution has typically been assumed to be uniform within the riparian area of interest (McDade et al., 1990, Van Sickle and

Gregory, 1990, Beechie et al., 2000, Cross, 2002, Welty et al., 2002). Although the same distribution was assumed for perpendicular tree distances from a stream in all cases, the manner in which it was used differed among the models. The majority of models (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) used the uniform distribution assumption to compute, and integrate, the LWD contribution as a continuous value throughout a riparian buffer of fixed width. Cross (2002), on the other hand, used this assumption to identify the midpoint of a fixed width buffer as the average location of the trees when computing potential LWD contribution.

While the assumption of a uniform distribution may not be unwarranted, using it in a continuous manner to compute potential LWD contribution fails to recognize the discrete nature of tree placement relative to a stream and its effects on the production of LWDin an actual riparian forest. Similarly, the use of a single distance from a stream, or several distances, for tree placement to compute potential LWD contribution over simplifies the relationships between tree placement relative to a stream and LWD production in an actual riparian forest. Further, this use may not be wholly justified by the assumption of a uniform distribution. Individual tree placement relative to a stream, even if trees are distributed uniformly, has a significant impact on the potential production of LWD. An LWD availability or recruitment model capable of using individual tree distances from a stream, recognizing the discreteness of the trees as well as their locations, is therefore desirable.

1.4 Individual tree or aggregated

LWD production models may be based on the positions and sizes of individual trees within a riparian area, but they have more commonly been based on *a priori* aggregations within the riparian area. Two types of aggregation have generally been used: tree aggregation and area aggregation, and they are frequently combined. Tree aggregation uses a single tree, or an average tree, to represent multiple trees for some specified area Cross (2002), and area aggregation assumes uniform properties, e.g., probability of stream intersection or tree height, within a particular region, or set of regions, (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002). The cited models were identified with the aggregation type that we felt best represented their underlying structures, but all of the models had some aspects of both forms of aggregation. The model of Van Sickle and Gregory (1990) aggregates both by area and tree, dividing a riparian area into strips of varying widths parallel to a stream and by tree height classes for different tree species.

Aggregated LWD models may not provide sufficient resolution for all applications, or they may require a large number of divisions, if, for example, a high spatial resolution was desired for determining the potential LWD contribution from a riparian buffer. Suppose we want a 3.3 ft resolution in perpendicular distance from a stream and tree height for a riparian forest containing ten tree species for a one acre buffer that was 170 ft wide, and assuming a maximum tree height of 164 ft. The model of Van Sickle and Gregory (1990) would require $10 \times 170/3.3 \times 164/3.3 = 25601$ individual distance×height×species cells, a number that is likely to greatly exceed the number of trees from the acre that may be large enough to potentially contribute to LWD. Decreasing the spatial resolution by a factor of two, to a 6.6 ft resolution, reduces the number of cells dramatically, to 6400, which may still be large relative to the number of trees that could potentially contribute LWD. Increasing the spatial sizes of the cells, reducing their resolution, may require averaging over relatively large areas. This discounts the actual locations of the individual trees that could contribute LWD to a stream channel, distributing their contributions over the area represented by each cell.

The locations of individual trees relative to a stream in a managed riparian buffer are important from management, economic, and regulatory perspectives. Trees in managed riparian buffers will most likely be located to provide maximum benefit to an adjacent stream, to achieve regulatory compliance, or to minimize management costs, particularly for landowners who may, for simplicity, remove some or all of a riparian buffer area from active management. Models representing LWD production that account for the individual tree locations relative to a stream rather than using tree or area based aggregation may be preferable, from both biological and computational perspectives: each tree would represent itself, providing its own contribution to LWD, allowing for localized clumping or other discrete distributional characteristics, and the computational difficulty is proportional to the number of trees large enough to potentially contribute to LWD.

1.5 A simulation based model for LWD availability

As the factors affecting the development of models for estimating the potential production of instream LWD were discussed, a number of potential limitations to existing approaches were identified. We believe that an individual tree based simulation model for LWD availability may provide a means to eliminate the majority of the identified limitations. Such a model would take as input a tree list describing the sizes, species, and numbers of trees in a forested riparian stand adjacent to a stream. This approach is also consistent with the use of tree based forest growth simulators, which typically use tree lists to represent forest stands (Belcher et al., 1982, Donnelly, 1997, Hann et al., 1997). Potential LWD production for a riparian buffer region represented by a tree list would then be estimated by using the tree list directly with the following basic simulation algorithm.

1. Randomly place each tree relative to a stream within a well defined riparian buffer area using some distribution of tree distances from a stream. This may be a theoretical distribution, such as the uniform distribution, or an empirically derived distribution, if available.

2. Determine the probability of stream intersection based on a distribution for the possible tree fall directions for each tree, given their random locations relative to the stream.

3. Compute the desired potential LWD contribution for each tree. This may include computing the dimensions or volume of potential LWD pieces. This step may include a simulation component as well, for example to determine whether a tree produces multiple LWD pieces or a single piece.

4. Combine the LWD contributions from the individual trees to obtain the potential LWD contribution for the riparian buffer.

5. Repeat steps 1 through 4 a number of times, and compute a statistical summary, which could include the mean and standard deviation or an estimate of a potential LWD distribution, to obtain estimates of the desired potential LWD contribution.

By modeling LWD availability we eliminate the potential uncertainty introduced into LWD recruitment models by their use of tree fall rates and stand mortality to specify the potential production of instream LWD. By using the tree list we eliminate the need to assume a tree height, or size, distribution. We simply use the heights, or sizes, of the trees in the tree list. By placing each tree relative to a stream we acknowledge the discreteness of the trees, allowing their actual locations to influence their potential LWD contributions to a stream. Placing each tree relative to a stream also resolves a number of issues related to aggregation, particularly the averaging of potential LWD production over large regions.

A simulation model for potential LWD production may be specified by simply identifying a distribution for the tree fall direction, which influences the probability of stream intersection, a distribution for the tree distances from a stream, and a model for determining the potential LWD contribution from each tree in a tree list. Variability in the values of potentially available LWD man then be estimated directly from the simulations, requiring no additional distributional assumptions. Finally, an LWD availability simulation model makes effective use of available data by directly using the individual trees from available tree lists and by permitting the distributions for tree fall direction and the distances of trees from a stream to be directly specified. As additional information about the production of instream LWD becomes available, assumptions about the tree fall direction or tree distances from a stream may be modified by changing their respective distributions.

In the next section, we describe a general framework specifying a simulation model for potential LWD production. The model described is an LWD availability model, but the framework could be readily modified for an LWD recruitment model. Following the description of the general simulation framework in Section 2, we applied the simulation model to estimate mean expected levels of potentially available LWD volume and piece count for natural, mature, Douglas-fir (*Pseudotsuga menziesii*) dominated riparian areas in western Washington. The general model was specialized to our application by specifying the requisite distributions and the procedures used to compute the potential LWD contribution from each tree. The application, its distributions, and procedures are described in Section 3. Data from Douglas-fir dominated stands in western Washington and western Oregon that were used to define tree lists for the LWD simulations are described in Section 4, followed by results of the simulations in Section 5. A brief discussion of the performance of the simulation model is provided in Section 6, followed by our concluding remarks.

2 Methods

Given the myriad factors influencing the probability of a tree falling and intersecting a stream to produce a large woody debris log, it would be difficult, if not impossible, to account for them all. We, therefore, do not directly address the possible physical causes for tree fall, or the probabilities of their occurrence, in the development of our model. Instead, we considered all standing, live trees as potentially contributing LWD to a stream based on an estimate of their probability of intersecting a stream *if* they were to fall. Our model, therefore, is a potential LWD availability model, providing estimates of the amount of LWD that *could* potentially be available for recruitment into a stream. The model does *not* estimate the amount of LWD that *has* been recruited into a stream or that *would* be recruited into a stream.

A simulation framework was selected for our model since the same forest structure, as represented by the numbers and sizes of trees in a riparian area could produce a variety of LWD amounts and LWD log sizes, depending on the locations of the individual trees relative to a stream. We emphasized the distributional aspects of the primary factors influencing the production of LWD: the probability of stream intersection for each tree, the location of each tree relative to a stream, and the presence of trees of differing sizes in a riparian area. The essential characteristics of our model may be modified by simply changing the shapes of the distributions associated with the model characteristics.

The simulation model we developed to obtain estimates of potentially available LWD has six components: 1) a submodel for generating potential stream intersecting logs, computing their sizes and volumes, and identifying potential LWD logs and potential functional LWD logs for different stream sizes; 2) a submodel specifying the probability of stream intersection for standing live trees; 3) a submodel for the distribution of tree fall directions relative to a stream; 4) a submodel for the distribution of the perpendicular distances of trees from a stream; 5) procedures for computing expected values for LWD volume and piece count using stream intersection probabilities; and 6) a simulation procedure used to obtain estimates of the expected, potentially available LWD volume or piece count, and approximations to their distribution. The specific objectives for the potential LWD availability simulation model are defined next in Section 2.1, followed by definitions and notation in Section 2.2, and then by descriptions of the LWD simulation model components. The components of the LWD simulation model are described, in turn, in Section 2.3 through Section 2.8.

2.1 LWD availability model objectives

The primary objectives for the LWD availability simulation model were provide a first order approximation to the LWD log generation processes for forests adjacent to streams and to produce estimates of the potentially available LWD log volume or number of pieces for a forested riparian area, or, equivalently, for a short section of a stream, that were in qualitative agreement with trends from available empirical studies (Bilby and Ward, 1989, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Fox, 2001). Quantitative agreement with empirical values was of lower importance, as it could be improved through refinements to the basic LWD availability simulation model.

The total number of LWD pieces and the total LWD volume produced by a forest adjacent to a stream were assumed to be independent of stream size across a landscape or within a sufficiently large region (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990). This assumption does not imply that LWD production is equal for all forest structures and all stream sizes. The LWD piece count and volume values clearly depend on the structural characteristics of a particular forest relative to a stream, e.g., the stand density, the tree size distribution, and the distances of the trees from a stream, or more simply whether the forest is old-growth, second growth, or a younger managed forest. Instead, the assumption implies that the distribution of LWD piece count or volume values that may be produced by a particular forest structure does not vary as a function of stream size. For example, all old growth riparian forests within a particular region have the same potential to produce LWD for recruitment into a stream. Potentially available total LWD piece count and volume values will be referred to using the acronym ALWD.

The number of functional LWD pieces and the sizes of functional LWD logs are known to vary by stream size (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Fox, 2001, Welty et al., 2002). The frequency of LWD logs providing for stream functions, e.g., pool creation, is lower for larger streams than for smaller streams and these LWD logs are also larger (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Fox, 2001, Welty et al., 2002). This implies that the number of LWD logs produced by a forest that is adjacent to a stream is greater than the number of LWD logs that function within a stream. The average size of available LWD logs produced by a forest adjacent to a stream is smaller than the average size of the functioning LWD logs. Given this dependence of functional LWD pieces or volume on stream size, a potentially available functional LWD log for a particular stream size is assumed to be a potentially available LWD log that is sufficiently large, that is, an available LWD log exceeding some minimum log diameter and log length, or volume, requirement (Beechie et al., 2000, Welty et al., 2002). Potentially available functional LWD piece count and volume values computed using a specified set of minimum LWD log sizes for different stream size classes will be referred to using the acronym AFLWD.

2.2 Definitions and notation

We now define the fundamental concepts and basic notation used to specify the LWD simulation model. For a tree in a forested area adjacent to a stream, let D^{dbh} be its diameter at breast height (DBH), H be its total height, and d be its perpendicular distance, measured from the center of the base of the tree at ground level, to a stream. We assumed that the tree DBH was positive, $D^{\text{dbh}} > 0$, since trees having heights less than breast height contribute little, if any, LWD to a stream. This implies that total tree height must be at least breast height, $H >= 4.5$ ft. We also assumed that the perpendicular distance of a tree to a stream was nonnegative, $d \geq 0$, that is trees do not grow wholly within that stream.

Let f_{taper} be a taper function giving the diameter D of a tree at any height h above the ground for a tree having a DBH of D^{dbh} and a height H, where $D = f_{\text{taper}}(h; D^{\text{dbh}}, H)$ and $0 \leq h \leq H$. We assume that the taper function f_{taper} is continuous and monotonically decreasing in the interval $[0, H]$, and that $f_{\text{taper}}(H; D^{\text{dbh}}, H) = 0$. The inverse taper function f^{-1}_{taper}, then, exists, and gives the height above the ground h at which a diameter D occurs, $h = f^{-1}_{\text{taper}}(D; D^{\text{dbh}}, H)$. The volume V of a log from the bole of a tree between heights h_1 and h_2, $0 \leq h_1 \leq h_2 \leq H$ for a tree having a DBH of D^{dbh} and a height H is then given by Equation 1, where $k = \frac{\pi}{4 \cdot 144} = 0.005454$.

$$V(h_1, h_2; D^{\text{dbh}}, H) = k \int_{h_1}^{h_2} \left[f_{\text{taper}}(h; D^{\text{dbh}}, H) \right]^2 dh \tag{1}$$

The *effective height* of a tree, H^{eff}, was defined to be the height from the ground to a point on the tree where a minimum upper stem diameter, or effective LWD diameter, $D^{\text{eff}} \geq 0$, was reached (Robison and Beschta, 1990, Van Sickle and Gregory, 1990). If the minimum effective diameter is zero, $D^{\text{eff}} = 0$, then the effective height is equal to the total tree height, $H^{\text{eff}} = H$. If the base diameter of the tree, the diameter at the ground or $h = 0$, is less than the minimum effective LWD diameter, $f_{\text{taper}}(0; D^{\text{dbh}}, H) \leq D^{\text{eff}}$, then the effective height of the tree was defined to be zero, $H^{\text{eff}} = 0$. The effective height for a tree was obtained using the inverse taper equation as in Equation 2.

$$H^{\text{eff}} = \begin{cases} f^{-1}_{\text{taper}}(D^{\text{eff}}; D^{\text{dbh}}, H), & \text{if } f_{\text{taper}}(0; D^{\text{dbh}}, H) > D^{\text{eff}} \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The use of a nonzero effective LWD diameter and the consequent effective height reduces the influence of the tops of trees when computing estimates of instream LWD. Very small pieces produced by the tops of trees intersecting a stream could substantially increase estimates of the number of instream LWD pieces while having little impact on the volume, or quality, of instream LWD since small pieces have very little volume. We wanted to avoid this situation, and used the effective LWD diameter and effective height to better identify the portion of a tree bole that could be considered as instream LWD.

The *potential stream intersection region* for a tree having an effective height H^{eff}, located a perpendicular distance d from a stream, where $d < H^{\text{eff}}$, was defined as the set of tree fall directions θ that could lead to a stream intersection, independent of any particular distribution of fall directions. Trees were assumed to be able to fall in any direction, so the range of possible fall directions is 360 degrees or 2π radians. We defined the perpendicular fall direction toward a stream to be $\theta = 0$, giving $\theta \in [-180, 180]$ degrees, or $\theta \in [-\pi, \pi]$ radians, where we interpret positive fall directions as upstream and negative fall directions as down stream. A potential stream intersection region is shown in Figure 1. The circle centered at the tree, having a radius H^{eff}, identifies the region where the tree could fall, given our assumption that trees may fall in any direction θ in the interval $[-\pi, \pi]$. The potential intersection region is then delineated by the upstream and downstream radii, as indicated in the figure, where the effective height of the tree would just touch the stream. These are the limiting radii for the potential stream intersection region and define the range of tree fall directions, $\theta \in (-\alpha, \alpha)$, that could produce a stream intersection. The angle α is the angle from the perpendicular direction toward the stream, $\theta = 0$, to the upstream limiting radius, and will be referred to as the limiting stream intersection fall direction. Trees whose effective heights are less than their perpendicular distances from a stream, $H^{\text{eff}} < d$, are assigned limiting stream intersection fall directions of zero, $\alpha = 0$. The formula used to compute α is given in Equation 3.

$$\alpha = \alpha(d, H^{\text{eff}}) = \begin{cases} \arccos\left(\frac{d}{H^{\text{eff}}}\right), & \text{if } d < H^{\text{eff}} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

The value of α obviously depends on the effective tree height H^{eff} and the perpendicular distance from the stream d. Three trees with their potential stream intersection regions indicated are shown in Figure 2. For this figure an effective diameter of zero, $D^{\text{eff}} = 0$, was used, making the effective height equal to the total height of the tree. The three trees and their respective potential stream intersection regions demonstrate that the size of the potential stream intersection region varies based on both the distance from the stream and the tree height. Tree 2 has a much greater potential stream intersection probability than Tree 1, since it is much closer to the stream, and Tree 3 has no potential stream intersection region since its effective height is less than its distance from the stream, making it impossible for it to fall and intersect with the stream.

The impact of the effective LWD diameter D^{eff} and its influence on the effective height H^{eff} and the potential stream intersection region of a tree adjacent to a stream is shown in Figure 3. The figure indicates the potential stream intersection regions for three identical

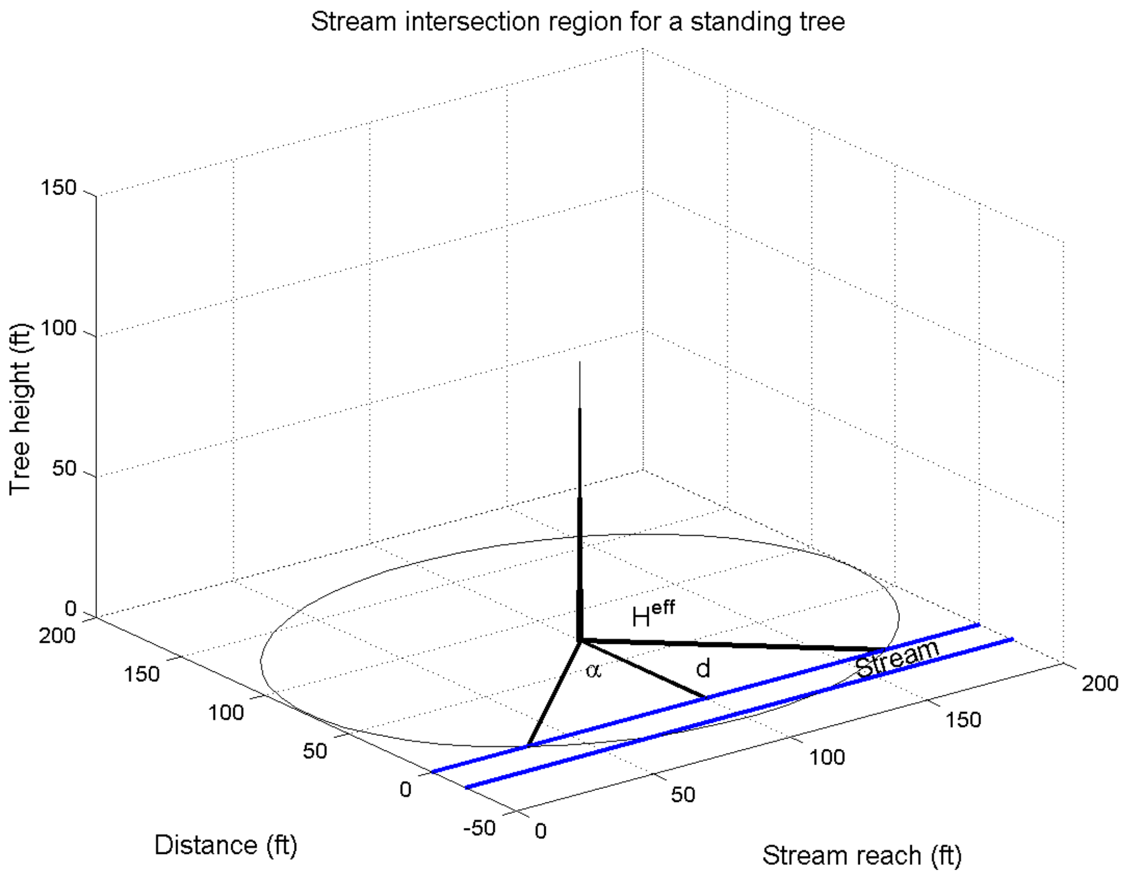

Figure 1: Diagram showing the potential stream intersection region assuming an arbitrary tree fall direction. The potential stream intersection region is delineated by the portion of the circle having a radius equal to the effective tree height H^{eff}, centered at the tree, between the two radial lines marking the range of stream intersecting fall directions.

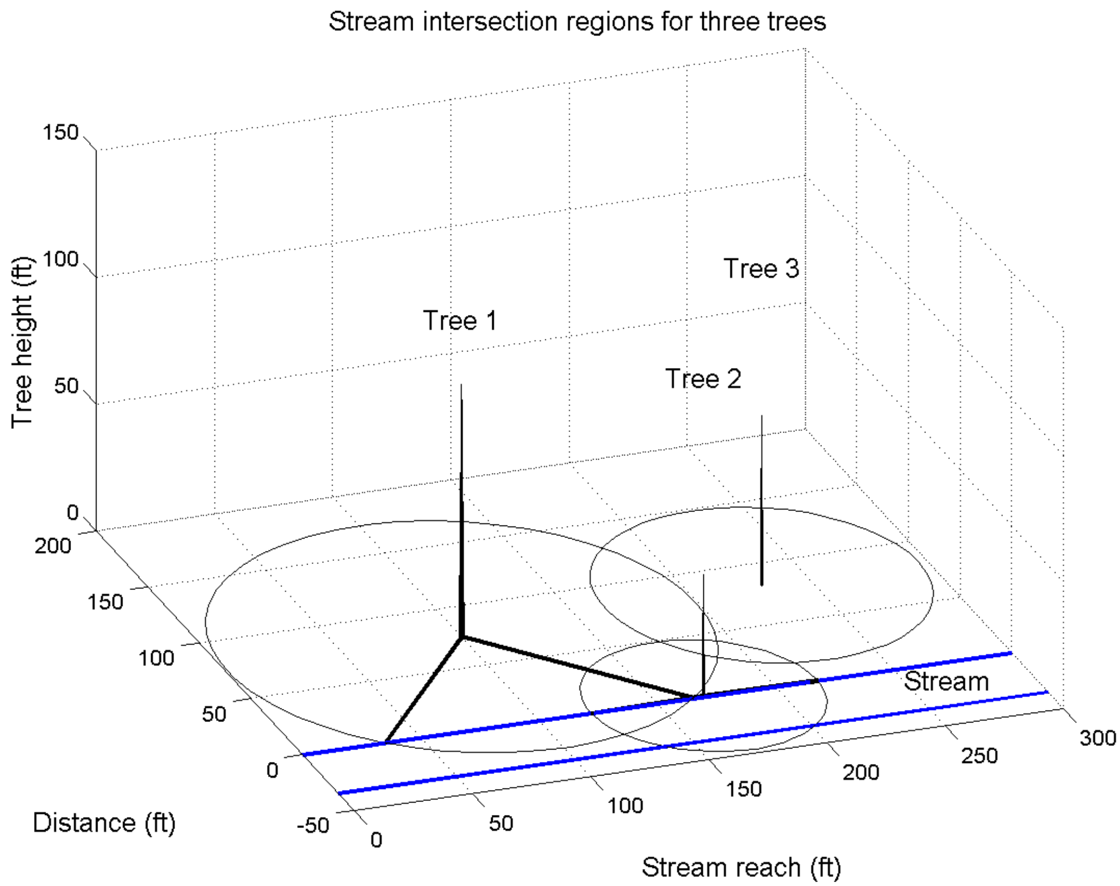

Figure 2: Three trees are shown with their stream intersection regions delineated. The distance of a tree from a stream and the effective tree height both influence the probability of a tree falling and intersecting a stream. Tree 1 and Tree 2 could fall and possibly intersect the stream, but Tree 3 will not: its effective height is less than its distance to the stream.

trees, located equal distances from an adjacent stream, for effective LWD diameters of $D^{\text{eff}} = 0$ inches, $D^{\text{eff}} = 4$ inches, and $D^{\text{eff}} = 8$ inches, from left to right. As the effective LWD diameter increases the effective height decreases, and the potential stream intersection region narrows and contracts toward the tree. In this example, the leftmost and center trees could fall and intersect the stream, their effective heights are greater than their distances to the stream, but the rightmost tree could not, as its effective height is less than its distance to the stream.

2.3 Log types, dimensions, and volume

To determine the size of a log produced by a tree that has fallen and intersected a stream we need a fixed point of reference relative to both the tree and the stream. The point of near bank stream intersection provides us with such a point of reference and we use it to derive the formulas used to compute the dimensions and volume of that segment of a bole of the tree that is to be considered a stream intersecting log. To proceed, we first identify the height on the tree bole where the point of stream intersection would occur, if the tree were to fall and intersect a stream. Next, we identify the portion of a stream intersecting log resting on the stream bank that is to be included. Finally, we specify the formulas used to compute the dimensions and volume of a stream intersecting log.

The height on the bole where a stream intersection would occur, H^{inter} depends on the direction of tree fall θ, where $\theta \in (-\alpha, \alpha)$ for a stream intersection, see Figure 1, and follows the relationship given in Equation 4.

$$H^{\text{inter}} = \frac{d}{\cos(\theta)} \tag{4}$$

If a tree were to fall perpendicular to a stream, $\theta = 0$, then the height where the near bank stream intersection would occur is simply the perpendicular distance to the stream, $H^{\text{inter}} = d$, but as θ increases or decreases away from zero, $\cos(\theta)$ decreases, and the height where the near bank stream intersection occurs would increase. For $\theta = \alpha$, the stream intersection height equals the effective height of the tree, and no stream intersecting log is produced. In the event that a tree is located very close to a stream, $d \approx 0$, and the fall angle was parallel or nearly parallel to the stream, $\theta \approx \frac{\pi}{2}$ we assumed that $H^{\text{inter}} = 0$, that is the entire bole of the tree from its base to its effective height was to be considered as the stream intersecting log.

The stability of instream LWD is an important factor for habitat, pool forming, and siltation (Bilby and Ward, 1989, 1991, Beechie et al., 2000). Given this importance, we may want to allow some part of a tree that is on the stream bank to contribute to the size of a stream intersecting log (Welty et al., 2002), since the part of the log that is on the bank will provide the majority of the stability. Let $H^{\text{offset}} > 0$ be the length of the portion of a

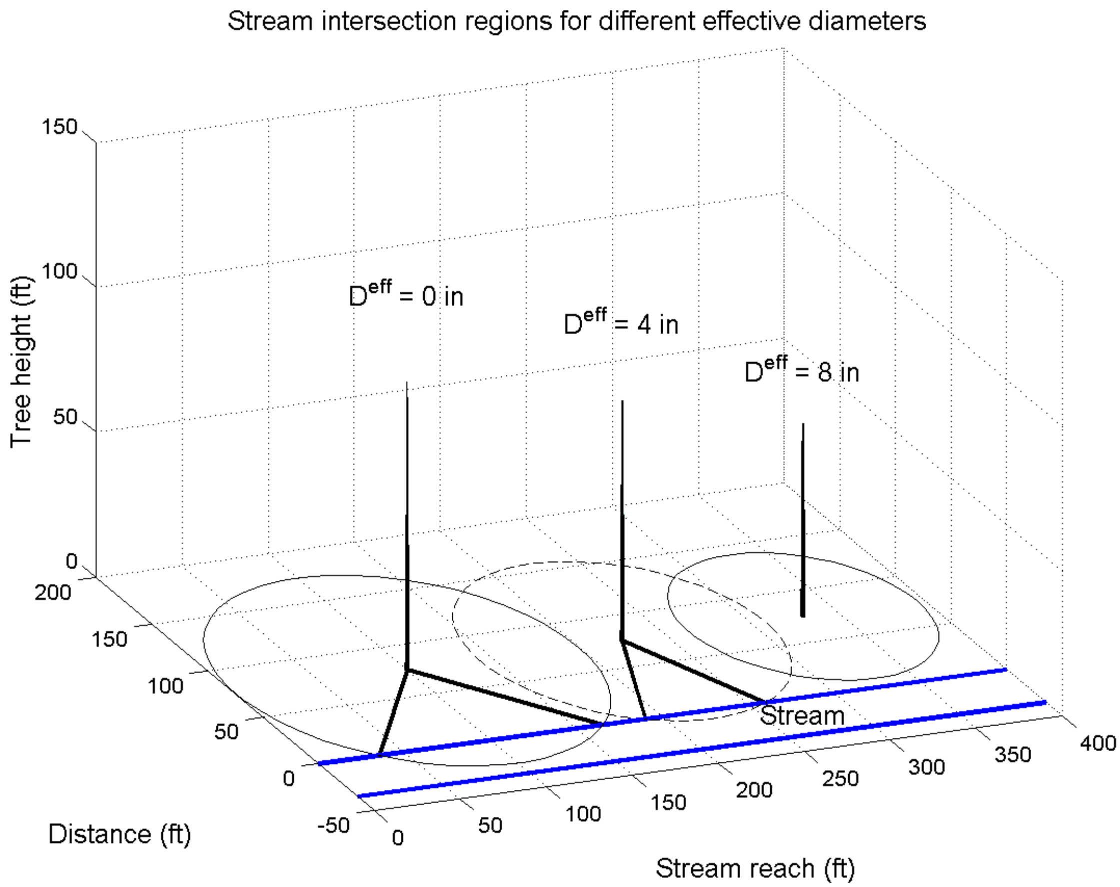

Figure 3: Stream intersection regions for effective LWD diameters of $D^{\text{eff}} = 0$ inches, $D^{\text{eff}} = 4$ inches, and $D^{\text{eff}} = 8$ inches, from left to right, for identical trees located the same distance from a stream. The leftmost and center trees could fall and intersect the stream, their effective heights are greater than their distances to the stream, but the rightmost tree could not, as its effective height is less than its distance to the stream.

stream intersecting log that rests on the stream bank, measured from the point of stream intersection H^{inter} toward the base of the tree. The height where the base of the stream intersecting log begins is then given by Equation 5, with the diameter at the base of the log given by Equation 6.

$$H^{\text{base}} = \begin{cases} H^{\text{inter}} - H^{\text{offset}}, & \text{if } H^{\text{inter}} > H^{\text{offset}} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

$$D^{\text{base}} = f_{\text{taper}}(H^{\text{base}}; D^{\text{dbh}}, H) \tag{6}$$

The value of H^{offset} was assumed to be fixed for all trees and all stream sizes. We recognize that this assumption may be too restrictive, since, for a stream intersecting log of fixed size, a greater portion of the bole on the bank would most likely be necessary to provide stability in larger streams, provided the log was large enough to remain stable on its own. We opted to impose consistency in the definition of a stream intersecting log across stream sizes, allowing the definition of functional LWD to incorporate factors related to stream size.

The dimensions of a stream intersecting log may then be defined by the base diameter of the log and its length, as given in Equation 7 and Equation 8, respectively, with the volume of the stream intersecting log given by Equation 9.

$$D^{\text{si}} = D^{\text{base}} \tag{7}$$

$$L^{\text{si}} = H^{\text{eff}} - H^{\text{base}} \tag{8}$$

$$V^{\text{si}} = V(H^{\text{base}}, H^{\text{eff}}; D^{\text{dbh}}, H) \tag{9}$$

The relationships among a standing live tree, its effective height and potential stream intersection region, based on an effective diameter of $D^{\text{eff}} = 4$ inches, a perpendicular tree fall, and the resulting stream intersecting log for $H^{\text{offset}} = 0$, are presented as a schematic diagram in Figure 4. Only the bole of a tree, without breakage, is considered as potentially contributing to LWD volume or piece count.

A *potential stream intersecting log* was defined to be the portion of the bole of a standing, live tree that could intersect a stream, *if* the tree were to fall in such a way as to intersect with a stream. The dimensions and volume of a potential stream intersecting log were defined as specified by Equation 4 through Equation 9.

A *potential LWD log* was defined to be a potential stream intersecting log whose base diameter and length simultaneously met or exceeded a minimum base diameter and length, $D^{\text{lwd}}_{\text{min}}$ and $L^{\text{lwd}}_{\text{min}}$, respectively, required of LWD logs. Potential stream intersecting logs not meeting the minimum size requirements to be considered as LWD were assumed to not contribute to LWD, and their log dimensions and volumes were assigned values of zero. The formulas used to identify potential LWD logs and to specify their base diameter, length, and volume are presented in Equation 10, Equation 11, and Equation 12, respectively.

$$D^{\text{lwd}} = \begin{cases} D^{\text{si}}, & \text{if } D^{\text{si}} \geq D^{\text{lwd}}_{\text{min}} \text{ and } L^{\text{si}} \geq L^{\text{lwd}}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

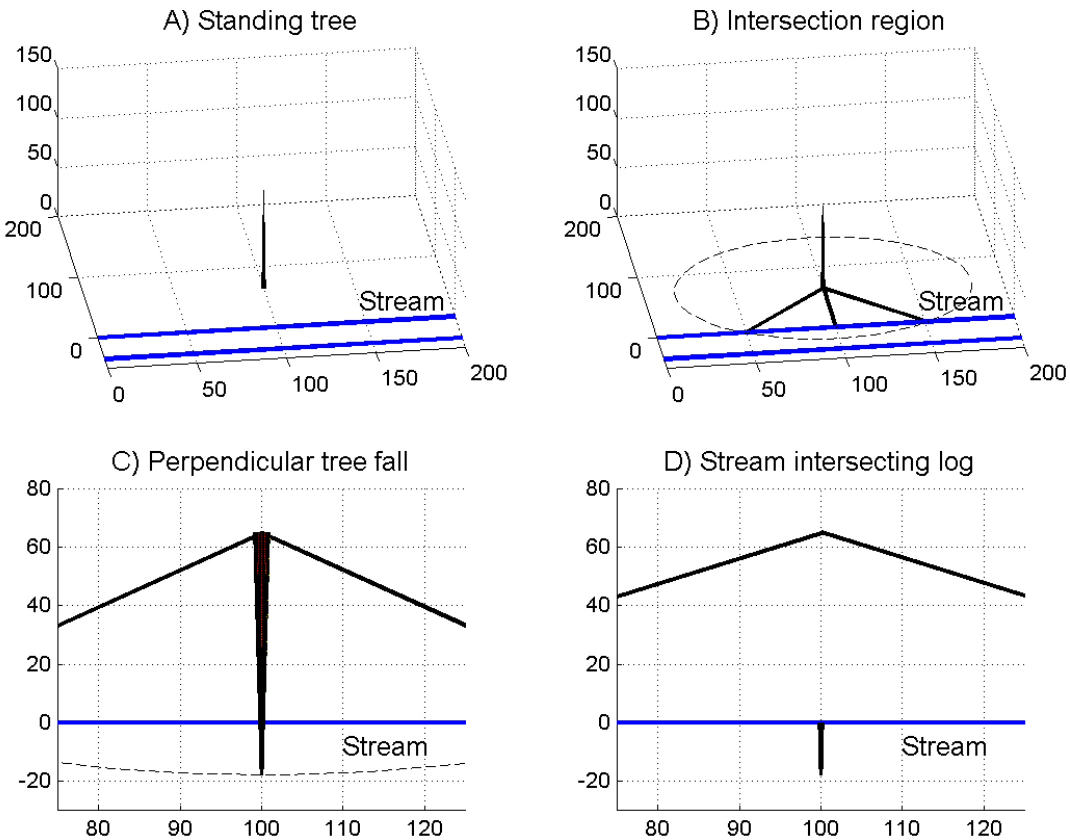

Figure 4: Schematic diagram showing a stream intersecting log that could have been produced by a falling tree. A) Standing tree: only the bole counts as LWD. B) The effective height and potential stream intersection region, $D^{\text{eff}} = 4$ inches. C) The tree falls perpendicularly and intersects a stream. D) The portion of the bole from the base height to the effective height is a stream intersecting log.

$$L^{\text{lwd}} = \begin{cases} L^{\text{si}}, & \text{if } D^{\text{si}} \geq D^{\text{lwd}}_{\text{min}} \text{ and } L^{\text{si}} \geq L^{\text{lwd}}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

$$V^{\text{lwd}} = \begin{cases} V^{\text{si}}, & \text{if } D^{\text{si}} \geq D^{\text{lwd}}_{\text{min}} \text{ and } L^{\text{si}} \geq L^{\text{lwd}}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

Values that have been used for $D^{\text{lwd}}_{\text{min}}$ and $L^{\text{lwd}}_{\text{min}}$ in the Pacific Northwest are 4 inches and 6.6 ft, respectively (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Fox, 2001, Welty et al., 2002).

A *potential functional LWD log* for a stream size class j, $j = 1, 2, \ldots, J$, where J is the number of stream size classes, was defined to be a potential LWD log whose base diameter and length simultaneously met or exceeded a minimum base diameter and length, $D^{\text{lwd},j}_{\text{min}}$ and $L^{\text{lwd},j}_{\text{min}}$, respectively, required of functional LWD logs for stream size class j, with $D^{\text{lwd},j}_{\text{min}} \geq D^{\text{lwd}}_{\text{min}}$ and $L^{\text{lwd},j}_{\text{min}} \geq L^{\text{lwd}}_{\text{min}}$. Potential LWD logs not meeting the minimum size requirements to be considered as functional for a particular stream size class were assumed to not contribute to functional LWD for that stream size class, and their log dimensions and volumes were assigned values of zero. The formulas used to identify potential functional LWD logs and to specify their base diameter, length, and volume are presented in Equation 13, Equation 14, and Equation 15, respectively.

$$D^{\text{lwd},j} = \begin{cases} D^{\text{lwd}}, & \text{if } D^{\text{lwd}} \geq D^{\text{lwd},j}_{\text{min}} \text{ and } L^{\text{lwd}} \geq L^{\text{lwd},j}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

$$L^{\text{lwd},j} = \begin{cases} L^{\text{lwd}}, & \text{if } D^{\text{lwd}} \geq D^{\text{lwd},j}_{\text{min}} \text{ and } L^{\text{lwd}} \geq L^{\text{lwd},j}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

$$V^{\text{lwd},j} = \begin{cases} V^{\text{lwd}}, & \text{if } D^{\text{lwd}} \geq D^{\text{lwd},j}_{\text{min}} \text{ and } L^{\text{lwd}} \geq L^{\text{lwd},j}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

Values for the minimum functional log diameter $D^{\text{lwd},j}_{\text{min}}$ and the minimum functional log length $L^{\text{lwd},j}_{\text{min}}$ used for stream size class j in the Pacific Northwest may, for example, be obtained from equations for minimum pool forming diameters (Beechie and Sibley, 1997, Beechie et al., 2000).

The definitions for a potential stream intersecting log, a potential LWD log, and a potential functional LWD log are nested, implying that the volume and number of potential stream intersecting logs are greater than or equal to the volume and number of potential LWD logs, which, in turn, are greater than or equal to the volume and number of potential functional LWD logs for a particular stream size class in a riparian forest. By using these definitions we are modeling the basic building blocks of instream LWD, the potential stream intersecting logs, which we then restrict to the subset of stream intersecting logs that may be considered as LWD or functional LWD within a stream. This process mimics the context within which samples of instream LWD are collected in empirical studies (Bilby and Ward, 1989, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Fox, 2001).

2.4 Stream intersection probability

We defined the *stream intersection probability* as the probability that a standing live tree in a forest adjacent to a stream could intersect the adjacent stream, *if* it were to fall. The stream intersection probability for a tree is clearly a fundamental characteristic, possibly the most fundamental characteristic, of the processes related to the production of LWD in streams. If a tree in a forest adjacent to a stream falls, regardless of the physical cause or causes of its fall, it will either intersect the adjacent stream or it will not, depending on the local physical environment of the tree, the fall direction of the tree, the size of the tree, in particular its height, and the distance of the tree from the stream.

The local physical environment of a tree may strongly influence the probability of stream intersection. For example, a tree having other trees located between it and a stream will have a lower probability of stream intersection than a tree having no intervening trees between it and a stream: the tree may fall and hit other trees which could deflect it away from the stream, or the tree could become hung up in the branches of the intervening tree. A falling tree that hits other trees could also increase their probability of intersecting a stream. Prevailing winds directed perpendicular to a stream could increase the number of trees falling towards a stream on one bank, increasing their probability of stream intersection, while decreasing the number of trees falling towards a stream on the other bank, and thereby decreasing their probability of stream intersection. Erosion of the stream bank directly adjacent to a stream would also increase the probability of trees falling into the stream. The importance of the stream intersection probability made its inclusion as a fundamental component of our LWD availability model essential.

We cannot take into account all of the factors that could possibly influence the stream intersection probability for a tree. A simplified description of the stream intersection probability that takes into account its most important factors is, therefore, necessary. We begin by assuming that there exists a regional stream intersection probability distribution for standing live trees in riparian forests that is averaged over the local physical environments of the individual trees in the riparian forests across the region. Averaging over the local physical environments of the trees to obtain a regional stream intersection probability distribution, allows us to focus our attention on a small number of factors that influence the stream intersection probability for a tree. We chose a three parameter representation of the stream intersection probability distribution, taking into account the tree fall direction, the size of a falling tree as indicated by its effective height, and the distance of a tree from a stream.

Let $f_{\text{intersect}}(\theta, d, H^{\text{eff}})$ be a continuous probability density function (PDF) describing the regional stream intersection probability for standing live trees in forested areas adjacent to a stream, where θ is the fall direction for the tree, d is the perpendicular distance of the tree from a stream, and H^{eff} is the effective height of the tree as defined in Equation 2. The PDF $f_{\text{intersect}}$ returns the likelihood that a tree of effective height H^{eff}, located a perpendicular distance d from a stream, and falling in a direction θ, relative to the perpendicular line between the tree and the stream, would intersect with the stream.

The stream intersection probability for a particular tree in a riparian forest may then be found by identifying the potential stream intersection region for the tree relative to its adjacent stream, as in Figure 1. Given the potential stream intersection region, defined by the limiting stream intersection fall directions $\pm\alpha$ from Equation 3, and the PDF $f_{\text{intersect}}$ defining the likelihood of stream intersection, the stream intersection probability p for a particular tree with an effective height H_0^{eff}, located a distance d_0 from a stream is given by Equation 16.

$$p = \int_{-\alpha}^{\alpha} f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}}) d\theta \tag{16}$$

2.5 Distribution of tree fall directions

The distribution of possible tree fall directions was assumed to depend on the tree size and perpendicular distance from a stream through the unknown PDF $f_{\text{intersect}}(\theta, d, H^{\text{eff}})$. For example, trees having a perpendicular distances from a stream exceeding their effective height, $d > H^{\text{eff}}$, cannot fall and intersect a stream, $f_{\text{intersect}}(\theta, d, H^{\text{eff}}) = 0$ for all fall directions θ, and trees having perpendicular distances from a stream that are smaller than their effective heights, $d < H^{\text{eff}}$, cannot intersect a stream if they fall away from it. The distribution of possible fall directions for a particular tree having an effective height H_0^{eff} that is a distance d_0 from a stream is the conditional fall direction distribution $f_\theta(\theta; d_0, H_0^{\text{eff}})$, based on the PDF $f_{\text{intersect}}(\theta, d, H^{\text{eff}})$, and defined by Equation 17,

$$f_\theta(\theta; d_0, H_0^{\text{eff}}) = f_\theta(\theta | d = d_0, H^{\text{eff}} = H_0^{\text{eff}}) = \frac{f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}})}{f_{d,H^{\text{eff}}}(d_0, H_0^{\text{eff}})} \tag{17}$$

for $f_{d,H^{\text{eff}}}(d_0, H_0^{\text{eff}}) > 0$, where $f_{d,H^{\text{eff}}}$ is the marginal PDF for distance from a stream d and effective tree height H^{eff}, and is defined in Equation 18.

$$f_{d,H^{\text{eff}}}(d, H^{\text{eff}}) = \int_{-\pi}^{\pi} f_{\text{intersect}}(\theta, d, H^{\text{eff}}) d\theta \tag{18}$$

A hypothetical fall direction distribution, scaled by a multiple of 100 to be visible on the axes, is given in Figure 5. For this example, trees are more likely to fall toward the stream than away from the stream, since the fall direction distribution peaks for the perpendicular tree fall direction, $\theta = 0$, and then tapers off to zero as θ increases or decreases.

2.6 Distribution of tree distances from a stream

The location of a tree relative to a stream is a critical factor in determining whether or not the tree may contribute to the potentially available LWD from the forested area adjacent

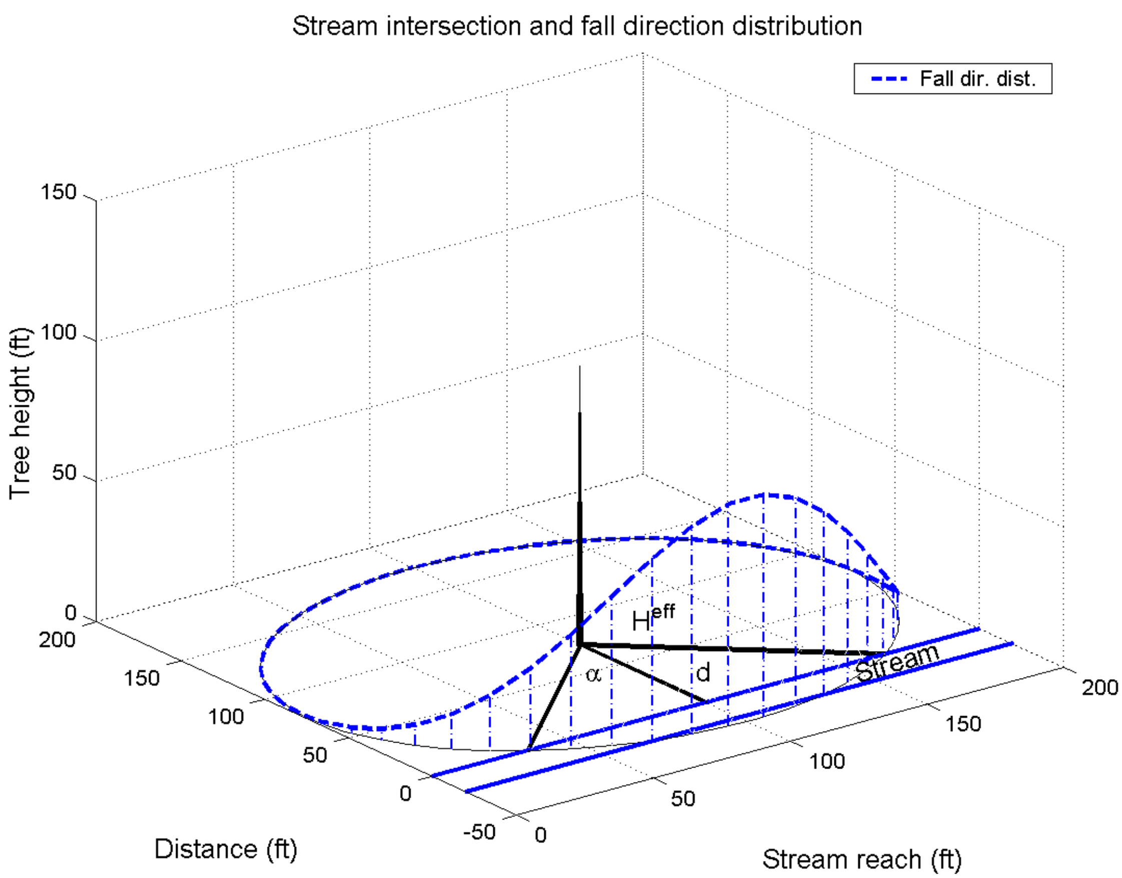

Figure 5: Diagram showing the potential stream intersection region with an hypothetical tree fall direction distribution. The fall direction distribution and the potential stream intersection region are used to compute a stream intersection probability for a tree.

to a stream that contains it. This is clearly demonstrated by the three trees in Figure 2 and by the dependence on the distance to the stream d in determining the potential stream intersection region, Equation 3 and the stream intersection probability, Equation 16. Given the importance of tree location to the production of LWD in a stream, the distance of a tree to its adjacent stream must be included as a component in a model for LWD production.

We assumed that there exists a regional distribution for the perpendicular distances of trees in riparian forests relative to an adjacent stream. We let $f_{\text{distance}}(d)$ be the PDF for the regional distribution of the perpendicular tree distances from their adjacent streams for $d \geq 0$. The PDF $f_{\text{distance}}(d)$ simply specifies the likelihood of finding a tree a distance d from a stream. The regional distribution of perpendicular distances may be thought of as a mixture distribution, $f(x) = \sum_{i=1}^{N_S} \alpha_i f_i(x)$, where N_S is the number of tree species found in the riparian areas of a region, and $f_i(x)$ represents the probability density function for the perpendicular distance to a stream for tree species i, and the α_i are weights giving the relative contribution of each species specific PDF $f_i(x)$ on the mixture distribution (Silverman, 1986, Duda and Hart, 1973).

If f_{distance} is used for multiple tree species or species groupings, e.g., coniferous species and hardwood species, then stream size may also be an important factor. For example, forests adjacent to small streams may be indistinguishable from upland or nonriparian stands in terms of species composition and tree location, but forests adjacent to large streams may have a greater proportion of hardwood species closer to the stream (Fox, 2003). This effect may be taken into account by adding a second parameter relating to stream size, e.g., bank-full width, W^{bf}, to the PDF, to obtain a two-dimensional distribution $f_{\text{distance}}(d, W^{\text{bf}})$.

The shape of the distribution of perpendicular tree distances from a stream, $f_{\text{distance}}(d)$, whether or not it takes tree species into account, may span a range from distributions that are skewed away from a stream, having more trees nearer to the stream than far away from it, to distributions that are skewed toward a stream, having fewer trees near to the stream than far away from it. A uniform distribution for $f_{\text{distance}}(d)$ may also occur and would indicate a lack of preference for tree location relative to a stream. If data for the perpendicular distances of trees from a stream are available they may be used to obtain an estimate of the distribution f_{distance}, either by calibrating an appropriate theoretical distribution by estimating its parameters, or by creating an empirical approximation to the distribution.

2.7 Expected values for LWD volume and piece count

The expected value $E(x)$ for a discrete random variable x is defined in Equation 19,

$$E(x) = \sum_{i=1}^{N} p_i \, x_i \tag{19}$$

where p_i is the probability of occurrence for the value x_i and N is the number of possible values for x (Bickel and Docksum, 1977, Mood and Graybill, 1963, Mardia et al., 1979). Expected ALWD and AFLWD piece count or volume values for a forested riparian area may be computed by matching the components of the expected value equation, p_i, x_i, and N, to their respective LWD counterparts for piece count and volume, and then substituting them into the expected value formula.

Let $T = \{T_1, T_2, \ldots, T_{N_T}\}$, be a tree list containing N_T standing, live trees representing a forested riparian area. Each measured tree T_i is assumed to be represented as a 4-dimensional vector $T_i = [N_i, D_i^{\text{dbh}}, H_i, d_i]^T$, where ^{T} indicates the transpose of a vector, and N_i is the number of live trees per acre (TPA) represented by tree i, D_i^{dbh} and H_i, are the DBH and height measurements, respectively, for tree i, and d_i is the average distance from a stream for the N_i trees represented by tree i, or simply the distance of tree i from a stream if $N_i \leq 1$. The number of trees contained in the riparian area represented by the tree list T is $\sum_{i=1}^{N_T} N_i$. These values provide the minimal set of measurements necessary to estimate expected values for potential LWD availability from individual trees.

To compute expected values for the potentially available LWD piece count and volume over the riparian area represented by the tree list T, the number of TPA represented by each tree, N_i, the volume of the potential LWD log produced by each tree, V_i^{lwd}, and the stream intersection probability, p_i for each tree are needed. The TPA was readily available from the tree list T, the volumes for potential LWD logs were obtained using the procedures defined in Section 2.3, and the stream intersection probabilities were obtained using the procedures defined in Section 2.4. In addition to the TPA, volume, and stream intersection probability, the base diameter and length, D_i^{lwd} and L_i^{lwd}, respectively, of the potential LWD log that each tree could have produced were also needed. These values were also obtained using the procedures defined in Section 2.3.

Formulas for identifying potential LWD logs and potential functional LWD logs from potential stream intersecting logs were provided in Section 2.3. The formulas used to compute expected values for ALWD or AFLWD were based on those for potential LWD logs and their dimensions, as defined by Equation 10 through Equation 12. The indicator function, defined in Equation 20, was used to identify potential LWD logs or potential functional LWD logs, based on the appropriate minimum LWD log dimensions, that contributed to the expected values. The indicator function simply returns a value of one if its first argument is greater than or equal to its second argument and a value of zero otherwise. When used in the expected value summations, the indicator function restricts the piece count and volume contributions to potential LWD logs for ALWD, and to potential functional LWD logs meeting the size requirements for a particular stream class for AFLWD. Use of the indicator function simplified the formulas used to compute the expected values, making the formula for the piece counts particularly convenient.

$$I(x,y) = \begin{cases} 1 & \text{if } x \geq y \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

Equations for computing expected values for LWD piece count and volume are presented for arbitrary values of $N_i > 0$, the number of TPA represented by tree T_i. If $N_i > 1$, the distance from the stream d_i was assumed to represent the average distance to the adjacent stream for all of the trees represented, and if $N_i < 1$, then d_i is simply the distance from the tree to the adjacent stream. This situation is representative of data obtained from a typical forest inventory where one or more samples were collected to estimate the per acre characteristics for a stand, or of output from a typical growth and yield model. If $N_i = 1$ for all trees, $i = 1, 2, \ldots, N_T$, then d_i is, again, simply the distance from the tree to the adjacent stream. This situation is representative of a complete inventory of all trees for a riparian area.

2.7.1 Computing expected potentially available LWD (ALWD)

All potential LWD logs contribute to the potentially available LWD piece counts and volumes. Potential LWD logs have base diameters that are least $D^{\min}$ inches and lengths that are at least $L^{\min}$ ft. Stream intersecting logs that were not large enough to be potential LWD logs were excluded from the computed expected values by using the product of the two indicator functions $I(D_i^{\text{lwd}}, D_{\min}^{\text{lwd}})$ and $I(L_i^{\text{lwd}}, L_{\min}^{\text{lwd}})$. The expected value for potentially available LWD volume may be computed by using Equation 21, and the expected value for the number of potentially available LWD pieces may be computed similarly as in Equation 22.

$$E(\text{ALWD}^V) = \sum_{i=1}^{N_T} p_i \cdot V_i^{\text{lwd}} \cdot N_i \cdot I(D_i^{\text{si}}, D_{\min}^{\text{lwd}}) \cdot I(L_i^{\text{si}}, L_{\min}^{\text{lwd}}) \tag{21}$$

$$E(\text{ALWD}^N) = \sum_{i=1}^{N_T} p_i \cdot N_i \cdot I(D_i^{\text{si}}, D_{\min}^{\text{lwd}}) \cdot I(L_i^{\text{si}}, L_{\min}^{\text{lwd}}) \tag{22}$$

2.7.2 Computing expected potentially available functional LWD (AFLWD)

Potential LWD logs are considered to be potential functional LWD logs for a particular stream class if the potential LWD log has a base diameter and length that are simultaneously greater than minimum functional LWD log dimensions specified for that stream class (Beechie et al., 2000, Welty et al., 2002). Let J be the number of stream size classes and define $D_{\min}^{\text{lwd},j} \geq D_{\min}^{\text{lwd}}$ and $L_{\min}^{\text{lwd},j} \geq L_{\min}^{\text{lwd}}$ to be the minimum base diameter and length, respectively, for a functional LWD log for stream class j. Potential LWD logs that do not simultaneously meet both the minimum diameter and length requirements are excluded in the expected value computations by using the product of the two indicator functions, $I(D_i^{\text{lwd}}, D_{\text{min}}^{\text{lwd},j})$ for the potential functional LWD log base diameter and $I(L_i^{\text{lwd}}, L_{\text{min}}^{\text{lwd},j})$ for the potential functional LWD log length.

The expected value for potentially available functional LWD volume and piece count for stream class j may be computed by using Equation 23 and Equation 24.

$$E(\text{AFLWD}_j^V) = \sum_{i=1}^{N_T} p_i \cdot V_i^{\text{si}} \cdot N_i \cdot I(D_i^{\text{lwd}}, D_{\text{min}}^{\text{lwd},j}) \cdot I(L_i^{\text{lwd}}, L_{\text{min}}^{\text{lwd},j}) \tag{23}$$

$$E(\text{AFLWD}_j^N) = \sum_{i=1}^{N_T} p_i \cdot N_i \cdot I(D_i^{\text{lwd}}, D_{\text{min}}^{\text{lwd},j}) \cdot I(L_i^{\text{lwd}}, L_{\text{min}}^{\text{lwd},j}) \tag{24}$$

2.8 Putting it all together: An LWD simulation model

For a given tree list $T = \{T_1, T_2, \ldots, T_{N_T}\}$ containing N_T standing live trees, representing a forested riparian area, where $T_i = [N_i, D_i^{\text{dbh}}, H_i, d_i]^T$, and N_i is the number of live TPA represented by tree i, D_i^{dbh} and H_i, are the DBH and height measurements, respectively, for tree i, and d_i is the average distance from a stream for the N_i trees represented by tree i, or simply the distance of tree i from a stream if $N_i = 1$, expected values for the potentially available LWD volume or piece count may be computed. Expected LWD values computed for the riparian area represented by the tree list T, however, are specific to the particular tree list and the distances of its trees from a stream. Expected values would, therefore, provide only a small part of the information regarding the potential for a riparian forest stand having a structure defined by the size and density components of the trees T_i in the tree list T, D_i^{dbh}, H_i, and N_i to potentially produce LWD.

We are interested not only in the expected values for the potentially available LWD, but also in the distribution of possible expected LWD values, and, in particular, the variability of those expected LWD values for a riparian forest stand having a structure defined by the size and density components of the trees in a tree list T that is representative of a typical forest inventory or the output of a growth and yield model. To better characterize the distribution of expected LWD values for a tree list T and their variability, a variety of tree location and tree fall direction configurations for the trees in the tree list T must be considered. A simulation model that randomly generates tree locations and tree fall directions for the trees in a tree list T was implemented to characterize the variability of the expected LWD values. Tree locations in the simulation model were based on the distribution f_{distance} for the perpendicular distance of a tree from a stream, and the tree fall directions in the simulation model were based on the distribution $f_\theta(\theta, d_i, H_i)$.

To simplify the presentation of the algorithm for the simulation model, let $G = G(T)$ be a function that returns the expected value, or vector of values, of interest for a particular tree list T, and let N_S be the number of simulation trials to be performed. For the simulation model we augmented the vector representing each tree $T_i = [N_i, D_i^{\text{dbh}}, H_i]^T$ and produced tree vectors T_{is}, for $s = 1, 2, \ldots, N_S$, that included the perpendicular distance of the tree from a stream d_{is}, the effective height H_{is}^{eff}, a tree fall direction θ_{is}, the stream intersection probability p_{is}, and the dimensions and volume of the potential LWD logs produced by each tree D_{is}^{lwd}, L_{is}^{lwd}, and V_{is}^{lwd} for each simulation trial, yielding augmented tree vectors

$$T_{is} = [N_i, D_i^{\text{dbh}}, H_i, d_{is}, H_{is}^{\text{eff}}, \theta_{is}, p_{is}, D_{is}^{\text{lwd}}, L_{is}^{\text{lwd}}, V_{is}^{\text{lwd}}]^T$$

to represent the trees in the tree list for a simulation trial s. The expected value, or values, computed by the function $G(T)$ may include the potentially available LWD or potentially available functional LWD obtained by using the appropriate formulas from Section 2.7, or other characteristics, such as cumulative LWD profiles perpendicular to a stream, or the average distance from a stream of trees that could contribute LWD. Using this notation, the algorithm used in the LWD simulation model is defined by the following steps.

1. Randomly generate perpendicular distances from a stream d_{is} from the distribution f_{distance} for each tree T_i in the tree list T and simulation trial s.

2. Compute the effective tree height H_{is}^{eff} and the limiting stream intersection fall directions $\alpha_{is} = \alpha(d_{is}, H_i^{\text{eff}})$ for each tree T_i in the tree list T using Equation 2 and Equation 3, respectively. This defines the potential stream intersection region for each tree and simulation trial s.

3. Compute the stream intersection probability p_{is} using Equation 16 for each tree T_i in the tree list T and simulation trial s.

4. Randomly generate tree fall directions θ_{is} from the distribution $f_\theta(\theta, d_{is}, H_i^{\text{eff}})$ for each tree T_i in the tree list T and simulation trial s. The tree fall directions need only be generated for $\theta_{is} \in [-\alpha_{is}, \alpha_{is}]$, since the stream intersection probability already takes into account the fall directions that cannot produce a stream intersecting log.

5. Compute the dimensions, D_{is}^{lwd} and L_{is}^{lwd}, and volume, V_{is}^{lwd}, of the potential LWD log produced by each tree T_i using d_{is}, p_{is}, and θ_{is}, for each tree T_i in the tree list T and simulation trial s. Only trees that could produce a potential LWD log have nonzero values for D_{is}^{lwd}, L_{is}^{lwd} and V_{is}^{lwd}, all other trees have $D_{is}^{\text{lwd}} = 0$, $L_{is}^{\text{lwd}} = 0$ and $V_{is}^{\text{lwd}} = 0$.

6. Compute the desired expected value, or vector, $G_s = G(T_s)$, from the augmented tree list T_s, for simulation trial s.

7. Repeat steps 1 through 6 N_S times to obtain a set of estimates G_s, for the desired expected value or vector.

8. Compute the desired statistical summary using the expected values or vectors G_s. The statistical summary could consist of the mean and standard deviation for scalar values of G_s, the mean and covariance matrix for vectors G_s, an estimate of the distribution of the values of G_s, or some other relevant summary.

3 Application

As our application of the LWD simulation model, we computed estimates of regional averages for expected potentially available LWD volume and piece count values for moderate to highly productive Douglas-fir dominated, mature, natural (unmanaged) riparian forests in western Washington State and several stream size classes. In addition, we also computed estimates of accumulation profiles for potentially available LWD volume and piece count perpendicular to a stream to identify source distances from a stream for potential LWD recruitment. Our objectives when specifying the LWD simulation model were to keep the model simple and to obtain results that were consistent with the trends for LWD that have been reported in the literature (Bilby and Ward, 1989, McDade et al., 1990, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Fox, 2001). We also wanted to maintain compatibility with other LWD models that have been reported (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) so that we could compare our results with theirs. We were primarily interested in assessing the performance of the individual tree simulation procedures. More detail could be added at a later time to improve the approximations to the tree fall direction distribution and the distribution of perpendicular distances from a tree to a stream, as information about these distributions becomes available, to improve the quantitative accuracy of the model.

We begin by completely specifying an LWD simulation model in Section 3.1, including the riparian area, the distributions, and the minimum dimensions for functional LWD logs. We then define the procedures that were used to test the LWD simulation model in Section 3.2, including the methods we used to compute the mean expected values for the potentially available functional LWD and expected accumulation profiles for LWD volume and piece count perpendicular to a stream.

3.1 Using the LWD simulation model

In order to use the LWD simulation model that we have described, the riparian buffer area and the distributions for the stream intersection probability, the distribution of tree fall directions, and the distances of trees from a stream need to be specified. We also need to specify the taper equation, or equations, that will be used to compute the dimensions and volumes of potential stream intersecting logs and potential LWD logs. These aspects of the LWD simulation model, as well as additional assumptions, are specified in Section 3.1.1 through Section 3.1.7.

3.1.1 Riparian buffer area

We assumed that the riparian area of interest for the LWD simulations was a riparian buffer located immediately adjacent to one side of a stream that was one acre in size. The riparian buffer was assumed to have a width of 170 ft, measured perpendicular to the stream, and a stream reach of 256.2 ft, measured along the bank of the stream. The value of 170 ft for the buffer width was chosen based on the total width of a riparian buffer that would be required under the Forests and Fish Rules of Washington State (FFR, 1999) for highly productive sites, Douglas-fir (*Pseudotsuga menziesii*) site class II (King, 1966).

3.1.2 Stream intersection probability

For this application of the LWD simulation model, we assumed that the probability of stream intersection for a tree with effective height H_0^{eff} located a distance d_0 from a stream, $f_{\text{intersect}}(\theta, d_0, H_0)$, depended only on the fall direction θ and was uniform in the interval $[-\pi, \pi]$ (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002). This implies that $f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}}) = f_{\text{intersect}}(\theta) = \frac{1}{2\pi}$, for all distances from a stream d_0 and effective tree heights H_0^{eff}. The stream intersection probability is theefore independent of the tree location and tree size, other then through the potential stream intersection region. The stream intersection probability p for a tree of effective height H_0^{eff} located a distance d_0 from a stream is, then, given by Equation 25.

$$p = \int_{-\alpha}^{\alpha} f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}}) d\theta = \int_{-\alpha}^{\alpha} \frac{1}{2\pi} d\theta = \frac{2\alpha}{2\pi} = \frac{\alpha}{\pi} \tag{25}$$

Recalling that $\alpha = \alpha(d_0, H_0^{\text{eff}})$ is the limiting stream intersection fall direction for a tree of effective height H_0^{eff} a distance d_0 from a stream, we substitute the formula for α from Equation 3 into Equation 25 to obtain the formula in Equation 26 for computing a stream intersection probability when assuming a that the probability of stream intersection was dependent on θ alone and the fall directions were equally likely or uniformly distributed.

$$p = \begin{cases} \frac{1}{\pi} \arccos\left(\frac{d_0}{H_0^{\text{eff}}}\right), & \text{if } d_0 < H_0^{\text{eff}} \\ 0 & \text{otherwise} \end{cases} \tag{26}$$

Assuming that the stream intersection probabilities depend only on θ and that the fall directions were uniformly distributed is equivalent to assuming that trees fall independently of one another. The uniform distribution of tree fall directions implies that only the geometry of the tree location and the tree size influence the stream intersection probability. The local physical environment of the tree, including other trees that may be present, therefore, has no impact on the stream intersection probability, and trees intersect with the stream independently of one another.

3.1.3 Distribution of tree fall directions

The conditional distribution of tree fall directions $f_\theta(\theta; d_0, H_0^{\text{eff}})$ takes a particularly simple form when the stream intersection probability distribution depends only on the tree fall direction. Recalling that

$$f_\theta(\theta; d_0, H_0^{\text{eff}}) = f_\theta(\theta | d = d_0, H^{\text{eff}} = H_0^{\text{eff}}) = \frac{f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}})}{f_{d,H^{\text{eff}}}(d_0, H_0^{\text{eff}})}$$

and that

$$f_{d,H^{\text{eff}}}(d, H^{\text{eff}}) = \int_{-\pi}^{\pi} f_{\text{intersect}}(\theta, d, H^{\text{eff}}) d\theta,$$

we see that

$$f_{d,H^{\text{eff}}}(d, H^{\text{eff}}) = \int_{-\pi}^{\pi} f_{\text{intersect}}(\theta, d, H^{\text{eff}}) d\theta = \int_{-\pi}^{\pi} f_{\text{intersect}}(\theta) d\theta = 1 \tag{27}$$

and that

$$f_\theta(\theta; d_0, H_0^{\text{eff}}) = f_\theta(\theta) = \frac{f_{\text{intersect}}(\theta)}{f_{d,H^{\text{eff}}}(d_0, H_0^{\text{eff}})} = \frac{f_{\text{intersect}}(\theta)}{1} = f_{\text{intersect}}(\theta). \tag{28}$$

The conditional distribution of tree fall directions as given in Equation 28 is, therefore, equal to the PDF for the stream intersection probabilities in this situation. The formulas in Equation 27 are simply a complicated way of restating our assumption that the stream intersection probabilities were independent of tree location and size.

3.1.4 Distribution of tree distances to a stream

We need to specify the regional distribution of perpendicular distances from the stream, $f_{\text{distance}}(d)$, for the trees located within our 170 ft wide one acre riparian buffer, located directly adjacent to a stream. The specific shape of this distribution is not known, and may vary with stream size and species, but the possible shapes are bracketed by distributions that are skewed toward the stream, having the majority of trees located further from the stream, and by distributions that are skewed away from the stream, having the majority of trees located nearer to the stream.

Given our uncertain knowledge of the shape of this distribution, we assumed that it was a uniform distribution within the range of the riparian buffer width, that is, perpendicular distances from a tree to a stream are assumed to be distributed as $U(0, 170)$ random variables. This implies that the PDF of the perpendicular distance distribution is $f_{\text{distance}}(d) = \frac{1}{170}$. This assumption has also been used by others (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002), and our use of it here facilitates comparisons to their results.

3.1.5 Tree taper and volume of stream intersecting logs

A taper equation was necessary to obtain the base diameter, length, and volume of a potential stream intersecting log, D^{si}, L^{si} and V^{si}, respectively. We made the simplifying assumption that the bole shape for all tree species could be represented by a single taper equation when estimating the dimensions and volumes of potential stream intersecting logs. Taper equations for each species could have been used, and will be added at some future date, but our intent was to demonstrate the simulation aspects of the model, and a single taper equation was deemed sufficient for this purpose. We were primarily interested in Douglas-fir dominated riparian forests, and therfore chose a taper equation for Douglas-fir from the literature.

The taper equation we used to define the bole shape for all trees was the variable exponent taper equation for the inside bark diameter, D^{ib}, of Douglas-fir (Kozak, 1988, 1998). We used outer bark diameter, D^{ob}, derive log dimensions and volumes, and outer bark diameters were obtained by multiplying the inside bark diameter D^{ib} obtained from the taper equation by $1/r_{\text{ib/ob}}$ where $r_{\text{ib/ob}}$ is the ratio of the inside bark diameter to the outside bark diameter. A value of $r_{\text{ib/ob}} = 0.91$ was used (Goudie, 1993), which is consistent with the value of 0.9 that was used in (Welty et al., 2002), published after this work began. The formula for the inside bark taper equation is defined in Equation 29,

$$D^{\text{ib}} = f^{\text{ib}}_{\text{taper}}(h; D^{\text{dbh}}, H) = a_0 (D^{\text{dbh}})^{a_1} a_2^{D^{\text{dbh}}} X^{\left[b_1 z^2 + b_2 \ln(z+0.001) + b_3 \sqrt{z} + b_4 e^z + b_5 \frac{D^{\text{dbh}}}{H}\right]} \tag{29}$$

where a_0, a_1, a_2 and $b_1, b_2, b_3, b_4 b_5$ are regression coefficients; D^{dbh} is the outside bark diameter of a tree at breast height or the DBH, measured 4.5 ft above the ground; H is total tree height; z is relative tree height h/H for a height h above the ground, $0 \leq h \leq H$; $X = [1 - \sqrt{z}]/(1 - \sqrt{p})$, and p is a relative height constraint guaranteeing that $X = 1$ when $z = p$, providing a point where the exponent does not influence the inside bark diameter. Outside bark diameters were then obtained using EquationNoobdiam.

$$D^{\text{ob}} = f^{\text{ob}}_{\text{taper}}(h; D^{\text{dbh}}, H) = \frac{f^{\text{ib}}_{\text{taper}}(h; D^{\text{dbh}}, H)}{r_{\text{ib/ob}}} = 1.099 f^{\text{ib}}_{\text{taper}}(h; D^{\text{dbh}}, H) \tag{30}$$

Values for the regression coefficients are given in Table 1. The description of the Douglas-fir taper equation and the notation used were based on those in Kozak (1988).

Table 1: Regression coefficients and values for the variable exponent Douglas-fir taper equation taken from Kozak (1988).

Coefficient	Value	Coefficient	Value
a_0	1.02453	b_1	0.95086
a_1	0.88809	b_2	-0.18090
a_2	1.00035	b_3	0.61407
		b_4	-0.35106
		b_5	0.05686

The volume of potential stream intersecting logs were computed in three steps using the outside bark diameters obtained from Equation 30. First a cumulative volume profile based on the outside bark diameters was computed for a tree from the ground to the top of the tree. Second, cumulative volumes V^{base} and V^{eff} were obtained by linear interpolation of the cumulative volume profile for the tree heights H^{base}, the height where the log begins, and H^{eff}, the effective height of the tree, for a potential stream intersecting log. The two volumes were then subtracted to get the an estimate of volume of the potential stream intersecting log, $V^{\text{si}} = V^{\text{eff}} - V^{\text{base}}$.

The cumulative volume profiles for each tree were approximated using volume values computed for segments of the bole representing approximately 0.5 ft of tree height using Smalian's formula (Husch et al., 1993). The volume values for each segment were then summed to obtain the approximate cumulative volume profile for each tree, and then the values V^{base} and V^{eff}, and V^{si}.

For a tree having a DBH D^{dbh} and a total height H, the cumulative volume profile was computed in the following way. Let $N_V = 2 \cdot \text{Int}(H + 1)$ be the number of volume segments used to compute the cumulative volume profile, where $\text{Int}(x)$ returns the nearest integer to x, and let $\delta = H/N_V$ be the height of a volume segment. Define $h_i = i * \delta$, $i = 0, 1, 2, \ldots, N_V$ to be the heights delineating the N_V segments on the tree bole whose volumes are desired, and $D_i = f^{\text{ob}}_{\text{taper}}(h_i; D^{\text{dbh}}, H)$ as their corresponding outside bark diameters. Volumes for the bole segments v_i, $i = 1, 2, \ldots, N_V$, were then computed using Equation 31, with $k = \frac{\pi}{4 \cdot 144} = 0.005454$, and the cumulative volume profile V_i was then obtained using Equation 32 for $i = 1, 2, \ldots, N_V$.

$$v_i = k\left(\frac{D_{i-1}^2 + D_i^2}{2}\right)\delta \tag{31}$$

$$V_i = \sum_{j=1}^{i} v_i \tag{32}$$

For the volume computations we assumed that all trees fell perpendicular to the adjacent stream, $\theta = 0$. This assumption produces conservative, larger than would be expected, values for the potentially available LWD volume and piece counts. and may provide an approximate upper bound for the expected potentially available LWD values.

3.1.6 Computing expected values

When computing the expected values in the simulations we wanted to consider a riparian acre populated with actual trees, where each tree represented exactly one tree, rather than a riparian acre populated with statistical trees, where each tree could represent more than one tree or a fraction of a tree. While relevant, fractional trees are difficult to harvest, and we wanted to represent a physically realizable, rather than a theoretical, forested riparian area. With this in mind, when computing the expected values for the potentially available functional LWD volume and pieces with Equation 23 and Equation 24, respectively, we wanted to used $N_i = 1$ for all trees in the tree list T so that each tree represented exactly one tree per acre. The procedure we used to expand a treee list to obtain a tree list where each tree represented exactly one tree is described next.

A tree list T' having TPA values that were not all equal to one was converted into a tree list T having TPA values equal to one in the following way. For each tree T'_i in the tree list T', we rounded its TPA value N'_i to the nearest integer, $N_i^{\text{Int}} = \text{Int}(N'_i)$, and $\text{Int}(x)$ returns the nearest integer to x. Any tree whose rounded value equaled zero, $N_i^{\text{Int}} = 0$, indicating a fractional TPA value that was less than $\frac{1}{2}$, was assigned a value of $N_i^{\text{Int}} = 1$, since the tree was in the tree list T' and should be represented in the tree list T used in a simulation. Trees having rounded TPA values greater than one, $N_i^{\text{Int}} > 1$, were replicated N_i^{Int} times in the tree list T, each with a TPA value of $N_i = 1$ to maintain the appropriate degree of representation for the tree in the tree list T used in a simulation. The number of trees in the tree list T is then $N_T = \sum_{i=1}^{N'_T} N_i^{\text{Int}}$. The number of trees in the new tree list may not be equal to the number of trees represented in original tree list, $N_T \geq \sum_{i=1}^{N'_T} N'_i$ depending on the number of fractional TPA values N'_i for each tree in the original tree list T'.

3.1.7 Additional LWD simulation model assumptions

We have not yet made any explicit assumptions about the distribution of trees along a reach of stream. In the general model the influence of tree location and, implicitly, the distribution of trees along a reach of stream, on the stream intersection probability is represented by the PDF $f(\theta, d, H)$, which then influenced the distribution of tree fall directions $f_\theta(\theta, d_0, H_0)$. The uniform distribution that we have assumed for tree fall directions takes into account only the perpendicular distance from a stream and the tree height. It does not incorporate any information related to the distribution of trees along a reach of stream. We, therefore, made the additional assumption that the distribution of trees along a reach of stream is uniform. The tree distance from a stream and the the effective tree height are now sufficient to compute stream intersection probabilities. A number of additional simplifying assumptions have also been made, and they appear in the following list.

1. All trees are assumed to have a single bole.
2. The tree bole does not break.
3. Only the bole of a tree contributes to available LWD volume or piece count. LWD volume or pieces that could be obtained from tree branches is not considered. See Figure 4 A through D.
4. The ground surface adjacent to a stream is flat.
5. The bank of a stream may be represented by a straight line.
6. Only standing live trees may contribute to potentially available LWD pieces or volume. Trees that have died or already fallen are not considered.
7. Contributions of LWD to a stream are only from the forest directly adjacent to the stream. Log transport in the stream is not considered, nor is movement of fallen logs down a slope.

3.2 Testing the LWD simulation model

To test the performance of the LWD availability simulation model we considered six stream size classes, described in Section 3.2.1. For each stream size class we computed mean expected values and mean LWD accumulation profiles perpendicular to a stream for potentially available functional LWD. The procedures used to compute the mean expected values for potentially available functional LWD are described in Section 3.2.2, and the procedures used to compute mean cumulative profiles for potentially available functional LWD are described in Section 3.2.3. The simulations used to compute the mean mean expected values for potentially available functional LWD were independent of those used to compute mean cumulative profiles for expected potentially available functional LWD. We assumed that the potentially available LWD ALWD, was equal to the potentially available functional LWD AFLWD, for the smallest stream size classes, E and F. That is, the maximum expected values of potentially available LWD occur for the smallest streams.

The following notation was used to specify the procedures for computing the mean values and mean cumulative profiles for expected potentially available functional LWD. Let N_{TL} be the number of available tree lists T_l, each having N_{T_l} trees, $T_l = \{T_{l1}, T_{l2}, \ldots, T_{lN_{T_l}}\}$. Each tree in a tree list T_l was represented by a vector $T_{li} = [N_{li}, D_{li}^{\text{dbh}}, H_{li}]^T$ containing the number of TPA represented by the tree, N_{li}, the DBH of the tree, D_{li}^{dbh}, and the height of the tree, H_{li}.

Table 2: Minimum functional LWD log base diameters and lengths for six stream size classes. Minimum functional LWD base diameters were based on (Beechie and Sibley, 1997, Beechie et al., 2000) and minimum functional LWD lengths were based on (Fox, 2001) with adjustments.

Stream size class j	Stream class code c_j	Bank-full width (ft) W_j^{bf}	Minimum LWD base diam. (in) $D_{\mathrm{min}}^{\mathrm{lwd},j}$	Minimum LWD length (ft) $L_{\mathrm{min}}^{\mathrm{lwd},j}$
1	A	75.5	25.2	33.7
2	B	33.1	11.1	30.0
3	C	13.5	4.8	13.3
4	D	8.5	4.0	8.4
5	E	5.2	4.0	6.6
6	F	3.3	4.0	6.6

3.2.1 Stream size classes and minimum functional LWD dimensions

Stream size classes were identified by using the average bank-full width along a reach of stream (Bilby and Ward, 1989, 1991, Fox, 2001, Welty et al., 2002). Let J be the number of stream size classes, and define W_j^{bf} to be the bank-full width for stream size class j, where $j = 1, 2, \ldots, J$. Associated with each stream size class are a stream size class code c_j and minimum LWD log dimensions, diameter and length, $D_{\mathrm{min}}^{\mathrm{lwd},j}$ and $L_{\mathrm{min}}^{\mathrm{lwd},j}$, respectively, that are necessary for a log to be considered a functional LWD log for that stream class. Values for the minimum dimensions for functional LWD logs are presented in Table 2. The minimum dimensions of functional LWD logs for stream classes E and F are equal to the minimum dimensions for potential LWD logs, and may therefore be used to estimate potentially available LWD, ALWD.

3.2.2 Mean LWD volume and piece counts

For each available tree list T_l, $l = 1, 2, \ldots, N_{TL}$, the LWD simulation model described in Section 2.8 was used with $N_S = 25$ to obtain mean values and standard deviations for the expected potentially available functional LWD for each of the J stream classes listed in Section 3.2.1. Independent simulations were run for each tree list T_l to compute expected values for potentially available LWD volume and piece count. For each simulation trial s, $s = 1, 2, \ldots, N_S$, we obtained an augmented tree list T_{ls}, containing trees

$$T_{lsi} = [N_{li}, D_{li}^{\mathrm{dbh}}, H_{li}, d_{lsi}, H_{li}^{\mathrm{eff}}, \theta_{lsi}, p_{lsi}, D_{lsi}^{\mathrm{lwd}}, L_{lsi}^{\mathrm{lwd}}, V_{lsi}^{\mathrm{lwd}}]^T$$

and computed the expected LWD volume or piece count values $G_{ljs} = G(T_{ls}, D_j^{\min}, L_j^{\min})$ using Equation 33 or Equation 34, respectively.

$$G_{ljs} = G(T_{ls}, D_{\min}^{\mathrm{lwd},j}, L_{\min}^{\mathrm{lwd},j}) = \sum_{i=1}^{N_T} p_{lsi} \cdot V_{lsi}^{\mathrm{lwd}} \cdot I(D_{lsi}^{\mathrm{lwd}}, D_{\min}^{\mathrm{lwd},j}) \cdot I(L_{lsi}^{\mathrm{lwd}}, L_{\min}^{\mathrm{lwd},j}) \tag{33}$$

$$G_{ljs} = G(T_{ls}, D_{\min}^{\mathrm{lwd},j}, L_{\min}^{\mathrm{lwd},j}) = \sum_{i=1}^{N_T} p_{lsi} \cdot I(D_{lsi}^{\mathrm{lwd}}, D_{\min}^{\mathrm{lwd},j}) \cdot I(L_{lsi}^{\mathrm{lwd}}, L_{\min}^{\mathrm{lwd},j}) \tag{34}$$

Next, we computed estimates of the mean, $\bar{G}_{lj}$, and standard deviation, SD_{lj}, of the expected potentially available functional LWD for each tree list T_l and stream class j, from the N_S volume or piece count expected values G_{ljs}, using Equation 35 and Equation 36, respectively.

$$\bar{G}_{lj} = \frac{1}{N_S} \sum_{s=1}^{N_S} G_{ljs} \tag{35}$$

$$\mathrm{SD}_{lj} = \sqrt{\frac{1}{N_S - 1} \sum_{s=1}^{N_S} \left(G_{ljs} - \bar{G}_{lj}\right)^2} \tag{36}$$

Finally, we computed the regional mean $\bar{G}_j$ and standard deviation SD_j of the expected potentially available functional LWD volume and piece count for each stream class j using the mean values $\bar{G}_{lj}$ for each available tree list T_l and stream class, using Equation 37 and Equation 38, respectively.

$$\bar{G}_j = \frac{1}{N_{TL}} \sum_{l=1}^{N_{TL}} \bar{G}_{lj} \tag{37}$$

$$\mathrm{SD}_j = \sqrt{\frac{1}{N_{TL} - 1} \sum_{l=1}^{N_{TL}} \left(\bar{G}_{lj} - \bar{G}_j\right)^2} \tag{38}$$

3.2.3 Mean cumulative LWD profiles perpendicular to a stream

For each available tree list T_l, $l = 1, 2, \ldots, N_{TL}$, the LWD simulation model described in Section 2.8 was used with $N_S = 100$ to obtain mean values and standard deviations for the expected potentially available functional LWD cumulative profiles perpendicular to a stream for each of the J stream classes listed in Section 3.2.1. Independent simulations were run for each tree list T_l to compute the expected values for potentially available LWD volume and piece count. For each simulation trial s, $s = 1, 2, \ldots, N_S$, we obtained an augmented tree list T_{ls}, containing trees

$$T_{lsi} = [N_{li}, D_{li}^{\mathrm{dbh}}, H_{li}, d_{lsi}, H_{li}^{\mathrm{eff}}, \theta_{lsi}, p_{lsi}, D_{lsi}^{\mathrm{lwd}}, L_{lsi}^{\mathrm{lwd}}, V_{lsi}^{\mathrm{lwd}}]^T$$

and computed the expected cumulative LWD volume or piece count profiles perpendicular to a stream.

The cumulative LWD profiles have two components: a vector of distances from a stream and a corresponding vector of expected cumulative LWD volume or piece count values. To compute a mean profile for expected LWD volume or piece count across the simulation trials s, a consistent set of distances was necessary, since each simulated profile would have different simulated distances. We assumed that an evaluation interval of $\delta = 2$ ft would be sufficient to capture trends in the cumulative LWD profiles over the 170 ft width that was used for the one acre riparian buffer. Each cumulative LWD profile was therefore interpolated at the distances from the stream $d_k = (k-1)\delta$, $k = 1, 2, \ldots, K$, with $K = 86$ intervals, and $d_1 = 0$ ft and $d_K = 170$ ft.

For each tree list T_l and simulation trial s, we computed cumulative LWD profiles G_{ljs} for each stream class j, using the following algorithm to define the function $G(T_{ls}, D_{\min}^{\mathrm{lwd},j}, L_{\min}^{\mathrm{lwd},j})$. Each profile is defined by the distances d_k and $G_{ljs} = [G_{ljs1}, G_{ljs2}, \ldots, G_{ljsK}]^T$.

1. Sort the distances of the trees from a stream d_{lsi}, the stream intersection probabilities p_{lsi}, and the LWD log dimensions D_{lsi}^{lwd} and L_{lsi}^{lwd}, and the LWD log volumes V_{lsi}^{lwd} by distance from the stream to obtain d_i^{sort}, p_i^{sort}, D_i^{sort}, L_i^{sort} and V_i^{sort}.

2. Compute the expected cumulative LWD volume, EV_i^{cum}, and piece count, EN_i^{cum} values for each stream class j and each sorted distance d_i^{sort} using Equation 39 or Equation 40, respectively.

$$EV_{ji}^{\mathrm{cum}} = \sum_{k=1}^{i} p_k^{\mathrm{sort}} \cdot V_k^{\mathrm{sort}} \cdot I(D_k^{\mathrm{sort}}, D_{\min}^{\mathrm{lwd},j}) \cdot I(L_k^{\mathrm{sort}}, L_{\min}^{\mathrm{lwd},j}) \tag{39}$$

$$EN_{ji}^{\mathrm{cum}} = \sum_{k=1}^{i} p_k^{\mathrm{sort}} \cdot I(D_k^{\mathrm{sort}}, D_{\min}^{\mathrm{lwd},j}) \cdot I(L_k^{\mathrm{sort}}, L_{\min}^{\mathrm{lwd},j}) \tag{40}$$

3. Linearly interpolate the cumulative LWD volume or piece count profiles defined by the sorted tree distance from a stream d_i^{sort} and EV_{ji}^{cum} or EN_{ji}^{cum}, respectively, for the distances d_k, $k = 1, 2, \ldots K$ to obtain EV_{jk}^{cum} or EN_{jk}^{cum} for each stream class j.

4. Assign the interpolated cumulative volume or piece count values to G_{ljs} using Equation 41 or Equation 42, respectively.

$$G_{ljs} = [EV_{j1}^{\mathrm{cum}}, EV_{j2}^{\mathrm{cum}}, \ldots, EV_{jK}^{\mathrm{cum}}]^T \tag{41}$$

$$G_{ljs} = [EN_{j1}^{\mathrm{cum}}, EN_{j2}^{\mathrm{cum}}, \ldots, EN_{jK}^{\mathrm{cum}}]^T \tag{42}$$

Next, we computed estimates of the mean profiles, $\bar{G}_{lj} = [\bar{G}_{lj1}, \bar{G}_{lj2}, \ldots, \bar{G}_{ljK}]^T$, and standard deviations, $\mathrm{SD}_{lj} = [\mathrm{SD}_{lj1}, \mathrm{SD}_{lj2}, \ldots, \mathrm{SD}_{ljK}]^T$, of the expected potentially available functional LWD for each tree list T_l, stream class j, and distance d_k from the N_S volume or piece count profiles G_{ljs}, using Equation 43 and Equation 44, respectively.

$$\bar{G}_{ljk} = \frac{1}{N_S} \sum_{s=1}^{N_S} G_{ljsk} \tag{43}$$

$$\mathrm{SD}_{ljk} = \sqrt{\frac{1}{N_S - 1} \sum_{s=1}^{N_S} \left(G_{ljsk} - \bar{G}_{ljk} \right)^2} \tag{44}$$

The mean cumulative LWD profiles for each tree list T_l and stream class j, $\bar{G}_{lj}$, may be summarized in a number of ways to obtain estimates of regional LWD accumulation characteristics. For example, mean cumulative expected LWD profiles $\bar{G}_j = [\bar{G}_{j1}, \bar{G}_{j2}, \ldots, \bar{G}_{jK}]^T$, and standard deviations, $\mathrm{SD}_j = [\mathrm{SD}_{j1}, \mathrm{SD}_{j2}, \ldots, \mathrm{SD}_{jK}]^T$ could be computed for the potentially available functional LWD volume and piece count and each stream class j from the mean values $\bar{G}_{ljk}$ for each available tree list T_l, stream class j, and distance d_k, using Equation 45 and Equation 46, respectively. The regional mean profile values were computed on a percentage basis.

$$\bar{G}_{jk} = 100\% \frac{1}{N_{TL}} \sum_{l=1}^{N_{TL}} \frac{\bar{G}_{ljk}}{\bar{G}_{ljK}} \tag{45}$$

$$\mathrm{SD}_{jk} = 100\% \sqrt{\frac{1}{N_{TL} - 1} \sum_{l=1}^{N_{TL}} \left(\frac{\bar{G}_{ljk}}{\bar{G}_{ljK}} - \bar{G}_{jk} \right)^2} \tag{46}$$

We were particularly interested in the mean distance from a stream required to achieve a particular level of LWD volume or piece count accumulation for different stream sizes, as this statistic may be useful in determining buffer widths for streams. These distances may only be obtained for stream classes j and tree lists T_l for which the LWD volume and piece count was nonzero. Let N_{TL}^j be the number of tree lists having nonzero LWD volume and piece count values for stream class j, and let $l = 1, 2 \ldots, N_{TL}^j$ be an index for those tree lists. Let P be the percentage of the cumulative LWD for which a mean distance is desired, and let $k_{\min}$ be the index where the minimum value of the quantity given in Equation 47 occurs for stream class j and the mean LWD volume or piece count accumulation profile $\bar{G}_{lj}$ for tree list T_l.

$$100\% \frac{\bar{G}_{ljk}}{\bar{G}_{ljK}} - P, \; k = 1, 2, \ldots, K \tag{47}$$

The value of $k_{\min}$ gives the index where the simulated mean cumulative LWD volume or piece count percentage is closest to the desired accumulation percentage. Next, we assign the distance d_{lj}^P the value $d_{k_{\min}}$, $d_{lj}^P = d_{k_{\min}}$. Approximate means and standard deviations of the distances from the stream where P percent of the LWD volume or piece count occurs for stream class j were computed using Equation 48 and Equation 49, respectively.

$$\bar{d}_j^P = \frac{1}{N_{TL}^j} \sum_{l=1}^{N_{TL}^j} d_{lj}^P \tag{48}$$

$$\mathrm{SD}_j^P = \sqrt{\frac{1}{N_{TL}^j - 1} \sum_{l=1}^{N_{TL}^j} \left(d_{lj}^P - \bar{d}_j^P \right)^2} \tag{49}$$

If there were multiple minimum values, the smallest of the index values was assigned to k_{min}. This situation could occur if P falls exactly between two percent accumulation values, or if $P = 100\%$ and 100% of the cumulative volume or piece count occurs for a value of k that is less than K. Means and standard deviations for distances from the stream were computed for each stream class j using LWD accumulation percentages P of 50%, 80%, 85%, 90%, 95%, 99%, and 100%.

4 Data

To compute estimates of regional averages for potentially available LWD volumes and piece counts for moderate to highly productive Douglas-fir dominated, mature, natural (unmanaged) riparian forests in western Washington State we first needed to identify a reference data set that is representative of natural riparian areas in the region of interest, western Washington State. In selecting our reference data set we were strongly motivated by the approach established in the Forests and Fish Rules (FFR), the Washington Forest Practices Rules governing riparian forest management in Washington that were adopted in 2001 (WFPB, 2001). The FFR were based in large part on the Forests and Fish Report (FFR, 1999) and two scientific reviews of the report (Ehlert and Mader, 2000, Fairweather, 2001).

In particular, the FFR established the paradigm of using a quantitative description of riparian forest stand structure at a specified age, called a Desired Future Condition (DFC), to evaluate potential riparian forest management regimes (FFR, 1999, WFPB, 2001). The quantitative description of the desired riparian forest structures was obtained using a sample derived primarily from public data sources. Following this paradigm, a sample of forest stands that was considered to be representative of a natural (unmanaged) riparian forest condition was desired.

When searching for publicly available data sources for natural (unmanaged) riparian stands we discovered a paucity of data for western Washington State. The data that did exist were primarily from the Pacific Northwest Forest Research Station Forest Inventory and Analysis (PNWFIA) program and the Continuous Vegetation Survey (CVS) program of the Pacific Northwest Region (R6, Region 6). While data from these sources were nominally from riparian stands there were several potential issues with regard to their use. First, few of the sample plots from either the PNWFIA data or the CVS data were located directly adjacent to a stream. A definition of a riparian zone would, therefore, be required to select plots that were close enough to the stream to be considered riparian forest. Second, distances to the nearest stream were only available at a subplot level for the PNWFIA data, which used an hierarchical sampling strategy. Using the plot data identified by the riparian subplots within the PNWFIA data produced a sample size that was too small to be effective for our use. Using the riparian subplots directly produced an acceptable sample size, but required scaling the tree expansion factors to obtain per acre values. While scaling the subplot values would not be expected to introduce a bias, it would increase the observed variability. While these issues were not insurmountable, we chose to take a different approach to identify our reference data set.

If we consider forest structure to be determined by the number and sizes of the trees, independent of tree species, which seems reasonable from the perspective of LWD production, then for small streams the distribution of forest structures in upland, or nonriparian, stands should be similar to the distribution of forest structures of riparian stands, particularly if the stream is not large enough to create a gap in the canopy. Given this, we would expect that the range in forest structures for riparian stands should be well represented by the range in structures for upland or nonriparian stands, and that estimates of LWD derived from the upland stands would provide good estimates of LWD values for riparian stands. For larger streams, the ability of an adjacent forest to produce LWD is generally thought to be independent of stream size (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Welty et al., 2002); the effect of stream size relates to the sizes of LWD logs that are considered functional, e.g., pool forming logs (Beechie and Sibley, 1997), or logs providing other stream functions (Bilby and Ward, 1989, 1991). The use of upland, or nonriparian, forest structures for large streams should, therefore, also be reasonable. There is also some evidence indicating that differences between upland and riparian forests dominated by the same species may be small (Macdonald et al., 2004), lending further support to the use upland stands to estimate LWD characteristics for riparian stands. We, therefore, chose not to discriminate between upland and riparian stands when selecting data to define our reference condition.

The forest inventory data from version 1.4 the integrated database (IDB) produced by the Pacific Northwest Forest Research Station Forest Inventory and Analysis program of the U.S. Forest Service (Hiserote and Waddell, 2004) were used to used to define the reference condition for our LWD simulations. The IDB contains inventory data for California, Oregon, and Washington collected by the Forest Service and the Bureau of Land Management, including Forest Inventory and Analysis program of the Pacific Northwest Research Station (PNWFIA), the Continuous Vegetation Survey program of the Pacific Northwest Region (R6, Region 6), the Forest Inventory program of the Pacific Southwest Region (R5, Region 5), and the Natural Resource Inventory program of the Bureau of Land Management

(BLMWO, western Oregon districts only) (Hiserote and Waddell, 2004). The inventory data from these sources has been standardized to a uniform set of attributes and combined within the IDB to provide a high quality comprehensive database of forest inventory information for these states.

Sample plots within the IDB used to define our reference condition were selected by using the following criteria. Column names used in the IDB are shown in a courier font, e.g., `FOREST_TYPE`.

1. Plots were classified as timberland (`GLC` = 20).
2. Plots were located in western Washington or western Oregon.
3. Plots were at elevations less than 2500 ft.
4. The plot was classified as Douglas-fir (species code 202) dominant by the data column `FOREST_TYPE`.
5. The Douglas-fir basal area was at least 50% of the total basal area.
6. Plots had ages that were at least 100 years and less than 180 years, determined using FIA age codes, column `STAND_AGE`. The relevant FIA age codes were 11 to 17, inclusive, for age classes 100-109 years to 170 to 179 years.
7. Plots had no residual overstory trees identified. Residual overstory trees were assumed to be an indication of past management, so these plots were eliminated. Residual overstory trees were identified using the data column `STAND_POS`.
8. Plots had total volumes that were between 25% and 138% of the average volume of a normal, or fully stocked, stand as defined in McArdle and Meyer (1930). The average total volume for a normal stand was taken as 17240 $\mathrm{ft}^3\mathrm{ac}^{-1}$, and wasobtained from McArdle and Meyer (1930).

We included plots from western Oregon because there were only 31 plots meeting the criteria found in western Washington, a sample size that was to small to be effective for our purposes, and productive Douglas-fir dominated natural forests in western Washington and western Oregon should have similar characteristics. Finally, only trees having DBH values of at least 4 inches were included, since small trees do not contribute significantly to LWD. These criteria yielded 179 plots with 16625 qualifying trees.

The tree data from the selected sample plots provided the tree lists for our LWD simulations. We had $N_{TL} = 179$ tree lists (plots) T_l, distributed over western Oregon and western Washington, each having N_{T_l} trees, $T_l = \{T_{l1}, T_{l2}, \ldots, T_{lN_{T_l}}\}$. Each tree in a tree list T_l was represented by a vector $T_{li} = [N_{li}, D_{li}^{\mathrm{dbh}}, H_{li}]^T$ containing the number of TPA represented

Table 3: Numerical summary of the 179 Douglas-fir dominated plots.

Attribute	Mean	Std. Dev.	Minimum	Median	Maximum
Age^{mid} (years)	123.2	15.9	104.5	124.5	164.5
TPA	134.6	77.8	23.9	118.1	513.0
QMD (in)	20.3	5.3	10.2	20.1	34.4
H (ft)	98.9	26.3	43.0	98.0	174.5
H^{40} (ft)	143.3	20.8	87.2	145.0	204.8
BA ($\text{ft}^2\text{ac}^{-1}$)	256.0	68.6	103.3	259.7	404.9
Volume ($\text{ft}^3\text{ac}^{-1}$)	12767.6	4112.8	4428.9	12945.4	23513.5
Elevation (ft)	255.9	254.1	20.0	190.0	1598.0

by the tree, N_{li}, the DBH of the tree, D_{li}^{dbh}, and the height of the tree, H_{li}. A numerical summary of the age class midpoints Age^{mid}, stand density TPA, QMD, average height (H), height 40 (H^{40}), total basal area BA, total volume V, and elevation obtained from the $N_{TL} = 179$ sample plots is provided in Table 3. Attribute values for each plot that were used to obtain the summary presented in the table were computed using the following procedures.

Let $\text{Age}_l^{\text{lower}}$ and $\text{Age}_l^{\text{upper}}$ be the lower and upper bounds of the age class for plot l and ba_{li} be the basal area of tree i on plot l computed using Equation 50,

$$\text{ba}_{li} = k \cdot (D_{li}^{\text{dbh}})^2, \tag{50}$$

where $k = \frac{\pi}{4 \cdot 144} = 0.005454$. The age class midpoints for each plot were computed using Equation 51,

$$\text{Age}_l^{\text{mid}} = \frac{\text{Age}_l^{\text{lower}} + \text{Age}_l^{\text{upper}}}{2} \tag{51}$$

and the stand level characteristics TPA, QMD, and H, and volume were computed using the formulas in Equation 52 through Equation 55 for each plot.

$$\text{TPA}_l = \sum_{i=1}^{N_{T_l}} N_{li} \tag{52}$$

$$\text{BA}_l = \sum_{i=1}^{N_{T_l}} \text{ba}_{li} \cdot N_{li} \tag{53}$$

$$\text{H}_l = \frac{\sum_{i=1}^{N_{T_l}} H_{li} \cdot N_{li}}{\sum_{i=1}^{N_{T_l}} N_{li}} \tag{54}$$

$$\text{QMD}_l = \left(\frac{\sum_{i=1}^{N_{T_l}} (D_{li}^{\text{dbh}})^2 \cdot N_{li}}{\sum_{i=1}^{N_{T_l}} N_{li}} \right)^{\frac{1}{2}} \tag{55}$$

$$V_l = \sum_{i=1}^{N_{T_l}} V(0, H_{li}; D_{li}^{\text{dbh}}, H_{li}) \cdot N_{li} \quad (56)$$

Values of H^{40} for each plot were obtained by computing the average height of the 40 largest diameter trees per acre, or all trees if there were fewer than 40 trees per acre represented.

5 Results

Two sets of results from the LWD availability simulation model are presented. The first set of results characterizes the mean expected values for potentially available LWD volume and piece count for the six stream size classes ranging from 3.3 ft to 75.5 ft. The mean LWD results are presented in Section 5.1. The second set of results characterizes the mean cumulative LWD volume and piece count profiles perpendicular to a stream for the six stream size classes. The cumulative LWD profile results are presented in Section 5.2.

5.1 Mean expected LWD volume and piece count results

Simulation results for the expected, potentially available functional LWD volumes and piece counts appear in Section 5.1.1 and Section 5.1.2, respectively. Combined results for voluem and piece count are also presented in Section 5.1.3. The results were obtained for independent simulations of each of the available tree lists T_l. The expected LWD volume values and piece counts were obtained simultaneously for each simulation and all stream size class given in Table 2. The estimates of the potentially available functional LWD for the different stream size classes accumulate as the stream size, and the minimum dimensions of functional pieces, decrease. With each smaller stream size class we get an additional contribution of AFLWD volume or pieces from potential LWD logs that are included for the smaller stream size class, but were excluded for the larger stream size class. That is, the volumes and pieces contributing to AFLWD for stream size class A also contribute to AFLWD for stream size classes B through F, and the increment over the AFLWD of stream size class A for stream size class B contributes to stream size classes C through F, and so on.

5.1.1 LWD volume results

Mean values and standard deviations for the expected, potentially available functional LWD volumes appear in Table 4. The mean expected values for potentially available functional LWD volume ranged from a low of 801.0 ft^3ac^{-1} for the widest streams, stream class A, to a high of 1580.4 ft^3ac^{-1} for the narrowest streams, stream classes E and F. The median expected LWD volume values were all less than their corresponding means indicating that

Table 4: Mean values for potentially available functional LWD volume (ft^3ac^{-1}). Values are for one side of a stream and were computed using all 179 of the available tree lists. Stream bank-full widths ranged from 75.5 ft for stream class A to 3.3 ft for stream class F, see Table 2.

Stream	Mean expected LWD volume (ft^3ac^{-1}) summaries				
class	Mean	Std. Dev.	Minimum	Median	Maximum
A	801.0	800.3	17.9	502.8	4236.2
B	1536.1	824.4	117.5	1352.8	4555.1
C	1579.1	813.8	269.0	1392.9	4583.4
D	1580.2	813.5	271.3	1393.5	4584.0
E	1580.4	813.5	271.7	1393.6	4584.1
F	1580.4	813.5	271.7	1393.6	4584.1

the distributions of the simulated expected LWD volumes may be skewed toward larger values. Minimum values for the expected LWD volume ranged from a value of 17.9 ft^3ac^{-1} for the largest stream width, stream class A, to a value of 271.7 ft^3ac^{-1} for the smallest stream width, stream class F, tracking the trend of the mean values. Maximum values for the expected LWD volume ranged from a value of 4236.2 ft^3ac^{-1} to a value of 4584.1 ft^3ac^{-1}, and were appear to be consistent with having one tree list with a number of large trees producing the maximum expected LWD volume. Overall, LWD volume availability increased as stream size decreased from stream class A to stream class F, approaching a saturation point at approximately 1580.0 ft^3ac^{-1}.

Tree size and stand density are both factors that can have a dramatic impact on the production and availability of functional LWD. To examine the possible effects of these attributes expected potentially available functional LWD volumes from the individual simulations for each tree list T_l and stream classes A through D were plotted against height 40 and TPA in Figure 6 and Figure 7. Results for stream classes E and F are essentially identical to those for stream class D. The plotted values are means plus or minus one standard deviation computed using the $N_S = 100$ expected LWD volume values obtained from the simulated riparian stands generated from each tree list.

Expected values for potentially available functional LWD volume increased, on average, as the dominant tree height increased for all four stream classes, see Figure 6. This trend may be somewhat weaker for stream class A due to higher relative variability caused by many of the volume values bing smaller for this stream class than for the other stream classes, indicated by more points being located near the x-axis. The cumulative nature of the expected LWD volume values as stream size decreases is also readily apparent, when comparing stream class A with stream class B, where the lower edge of the data has been lifted away from the x-axis. Given the age selection criteria, we had few stands with dominant height less than 100 ft, but extrapolating the trend to younger stands with smaller trees, would indicate that small expected LWD volumes are likely for dominant heights less than 100 ft. Three outliers may also be present, appearing well above the data between dominant heights of approximately 125 ftand 175 ft. These three points were associated with stands of moderate to low densities but containing a number of very large trees.

Expected values for potentially available functional LWD volume were greatest for moderate stand densities, between, approximately, 50 TPA and 150 TPA, for all four stream classes, see Figure 7. Of particular interest is the range in expected LWD volume values within this range of stand densities, with a minimum near zero ft^3ac^{-1} for stream class A and a maximum that was over 4000.0 ft^3ac^{-1}. For the smaller stream classes the ranges were approximately 300.0 ft^3ac^{-1} to 4500.0 ft^3ac^{-1}. Expected LWD volume values were somewhat smaller for stream class A in this range than for the other stream classes, which was expected, and again we can see the incremental nature of the LWD volume as the stream size decreased, allowing smaller logs to contribute. The expected potentially available functional LWD volumes were generally smaller for lower stand densities, densities less than 50 TPA, and for higher stand densities, densities greater than 150 TPA. The trend in expected LWD volume decreased as stand density increased, but with some variability. The three possible outliers identified previously are not as apparent in this figure. In addition, as stand density increased the variability of the functional LWD volume estimates decreased as the volume decreased, indicating that as there are more, and smaller, trees to place relative to a stream, the influence on the expected LWD volume value of each tree is reduced.

5.1.2 LWD piece count results

Mean values and standard deviations for the expected, potentially available functional LWD piece counts appear in Table 5. The mean expected values for potentially available functional LWD pieces ranged from a low of 2.1 pieces ac^{-1} for the largest stream width, stream class A, to a high of approximately 17.6 pieces ac^{-1} for the smallest stream widths, stream classes, D, E, and F. The median expected LWD piece count values showed the same trend as the mean values, but were all smaller than their corresponding means. This implies that the distributions of the simulated expected LWD piece counts may be skewed toward larger values. Minimum values for the expected LWD piece counts followed the same trend as the mean values, ranging from 0.1 pieces ac^{-1} for the largest stream class to 6.5 pieces ac^{-1} for the smallest stream classes. Maximum values for the expected LWD piece counts increased rapidly from 7.4 pieces ac^{-1} for the largest stream width, stream class A, to 35.8 pieces ac^{-1} for the smallest stream width, stream class F. Overall, LWD piece count availability increased as stream size decreased from stream class A to stream class F, approaching a saturation point at approximately 17.6 pieces ac^{-1}.

To assess the possible impact of tree size and stand density on LWD piece count, expected

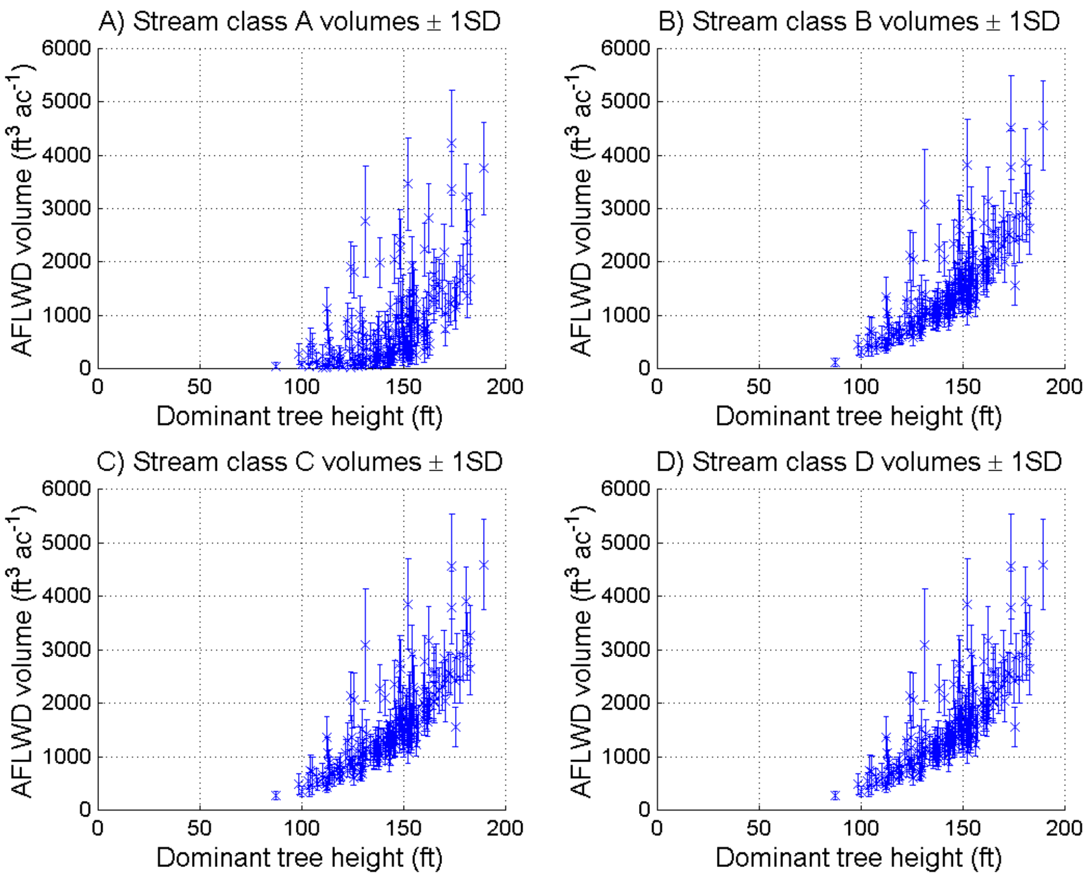

Figure 6: Expected values for potentially available functional LWD volume (ft^{3}ac^{-1}) for each tree list T_l and stream classes A through D plotted against dominant tree height. Values are means ± 1 std. dev. for one side of a stream, and were obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

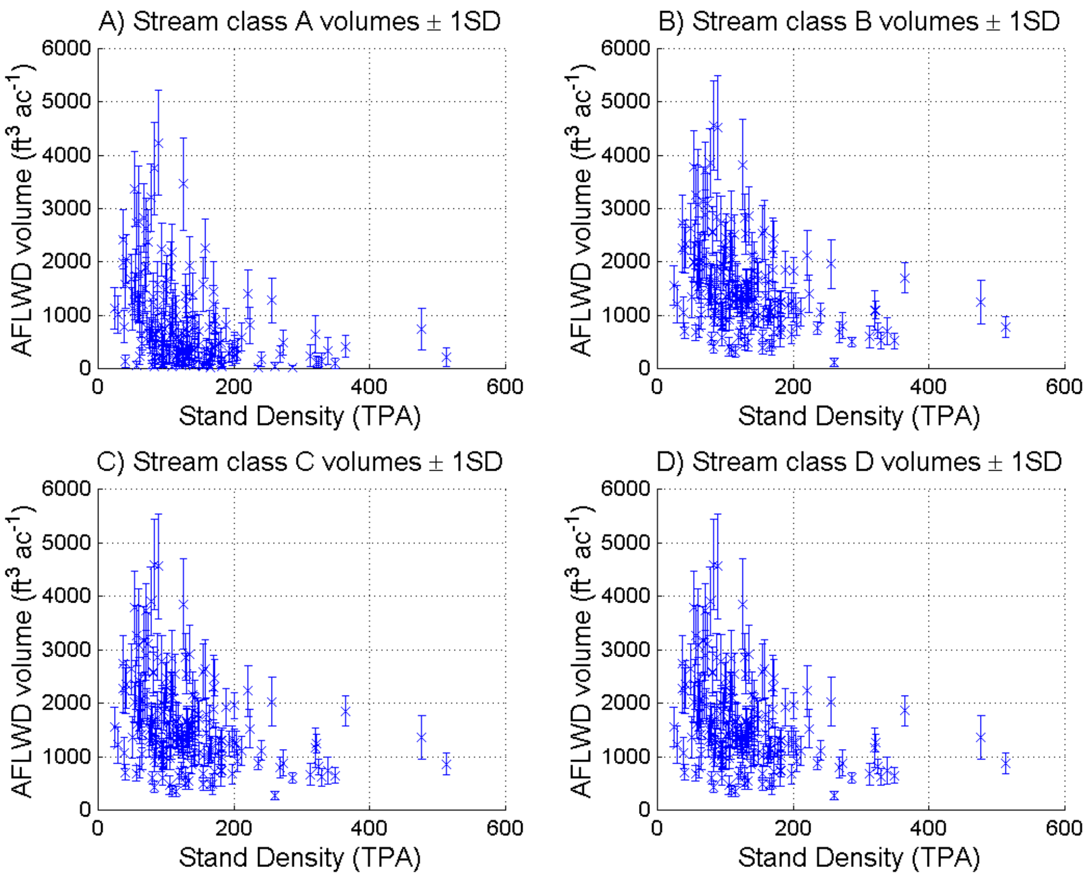

Figure 7: Expected values for potentially available functional LWD volume ($\mathrm{ft}^3\mathrm{ac}^{-1}$) for each tree list T_l and stream classes A through D plotted against stand density. Values are means $\pm$ 1 std. dev. for one side of a stream, and were obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

Table 5: Mean potentially available functional LWD piece count results (n ac^{-1}). Values are for one side of a stream and were computed using all 179 of the available tree lists. Stream bank-full widths ranged from 75.5 ft for stream class A to 3.3 ft for stream class F, see Table 2.

Stream class	Mean expected LWD piece count (n ac^{-1}) summaries				
	Mean	Std. Dev.	Minimum	Median	Maximum
A	2.1	1.7	0.1	1.6	7.4
B	11.7	3.8	2.5	11.9	20.5
C	16.7	5.2	6.3	16.6	33.3
D	17.4	5.5	6.4	17.1	35.1
E	17.6	5.6	6.5	17.2	35.8
F	17.6	5.6	6.5	17.2	35.8

potentially available functional LWD piece counts from the individual simulations for each tree list T_l and stream classes A through D are plotted against height 40 and TPA in Figure 8 and Figure 9. Results for stream classes E and F are essentially identical to those for stream class D. The values are means plus or minus one standard deviation computed using the $N_S = 100$ expected LWD piece count values obtained from the simulated riparian stands generated from each tree list.

Expected values for potentially available functional LWD piece counts increased, on average, as the dominant tree height increased for all four stream classes, see Figure 8. This is most noticeable for stream classes A and B, With stream classes C, and D showing much weaker trends due to greater variability. The cumulative nature of functional LWD piece count values is readily apparent when moving from stream class A to stream classes B and C, with piece counts increasing as stream size decreases. Given the age selection criteria, we had few stands with dominant height less than 100 ft. Extrapolating the observed trends to younger stands with smaller trees, would indicate that small values for expected LWD piece counts are likely for dominant heights less than 100 ft, particularly for larger streams. For smaller stream the range in AFLWD piece counts is quite wide, relative to the piece count values, possibly with a slight upward trend, throughout the range of dominant heights. There may also be a slight narrowing of the range for the plots with taller trees. Several outliers may also present, as seen in the figures for stream classes C and D. Three of them have piece count values exceeding 30 LWD pieces ac^{-1} for dominant heights between, approximately, 125 ftand 175 ft. An additional outlier may occur for 30 LWD pieces ac^{-1} and a dominant height near 85 ft. These points may, however, simply be near the outer edge of the envelope of the data.

Expected values for potentially available functional LWD piece counts were greatest for moderate stand densities, between 50 TPA and 150 TPA, for stream classes A and B, and

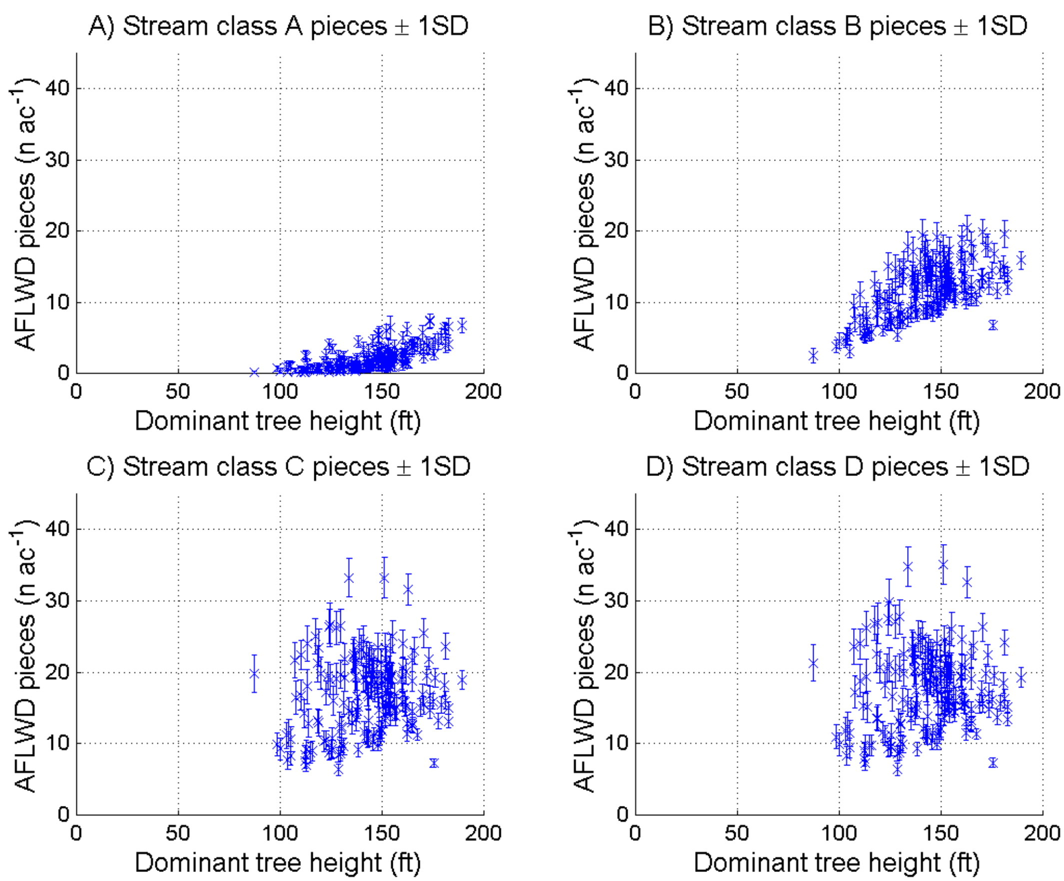

Figure 8: Expected values for potentially available functional LWD piece count (pieces ac^{-1}) for each tree list T_l and stream classes A through D plotted against dominant tree height. Values are means ± 1 std. dev. for one side of a stream, and were obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

generally increased, to a saturation point, throughout the range of stand densities for stream classes C and D, see Figure 9. The effects of the minimum functional LWD log dimensions and the cumulative nature of AFLWD for decreasing stream size are readily apparent when moving from a larger stream class to smaller stream classes. The functional LWD piece counts were smallest for the largest stream size, stream class A, having values that were less than 10 pieces ac^{-1}. Piece counts also clearly increased as the stream size decreased. For the largest stream classes, the expected potentially available functional LWD piece counts were lower for higher stand densities, densities greater than 200 TPA, particularly for stream class A where the highest stand densities have almost no available LWD. For the small stream sizes there appears to be a curvilinear relationship between stand density and the potentially available functional LWD piece count and stand density that increases with stand density to a saturation point for the smaller stream classes. Higher stand densities had an somewhat greater variability in their estimates of AFLWD piece counts, possibly due to differences in the tree size distributions among those tree lists.

5.1.3 Combined LWD volume and piece count results

The expected values for potentially available LWD volume and piece count are coupled, or dependent, attributes, and we now consider their joint characteristics. Scatter plots of the AFLWD volume *vs.* AFLWD pieces are presented in Figure 10. As stream size decreases the magnitude and range of the number of AFLWD pieces increases quite dramatically, moving from stream class A to stream class C, while the magnitude and range of the AFLWD volume values increases only moderately, most notably between stream classes A and B. The majority of potentially available LWD volume, then, is contributed by a relatively small number of large logs, given that the large increases in number of AFLWD pieces did not cause a corresponding increase in AFLWDvolume. Finally, the limits bounding the range in AFLWD volumes are relatively constant, ranging from 500.0 ft^3ac^{-1} to 3000.0 ft^3ac^{-1} for piece counts in the range from 5 pieces ac^{-1} to 15 pieces ac^{-1} for stream class B, and for piece counts in the range from 10 pieces ac^{-1} to 25 pieces ac^{-1} for stream classes C, and D. Equivalent AFLWD volumes may, therefore, be produced from quite different numbers of LWD pieces.

5.2 Mean expected cumulative LWD profile results

The cumulative LWD profiles were used to examine the mean values and the variability of the LWD volume and piece count accumulation percentages for fixed distances from a stream spanning the 170 ft width of our simulated one acre riparian buffers. The cumulative LWD profiles were also used to examine mean distances and the variability of the distances from a stream where fixed cumulative LWD volume and piece count percentages occurred. The

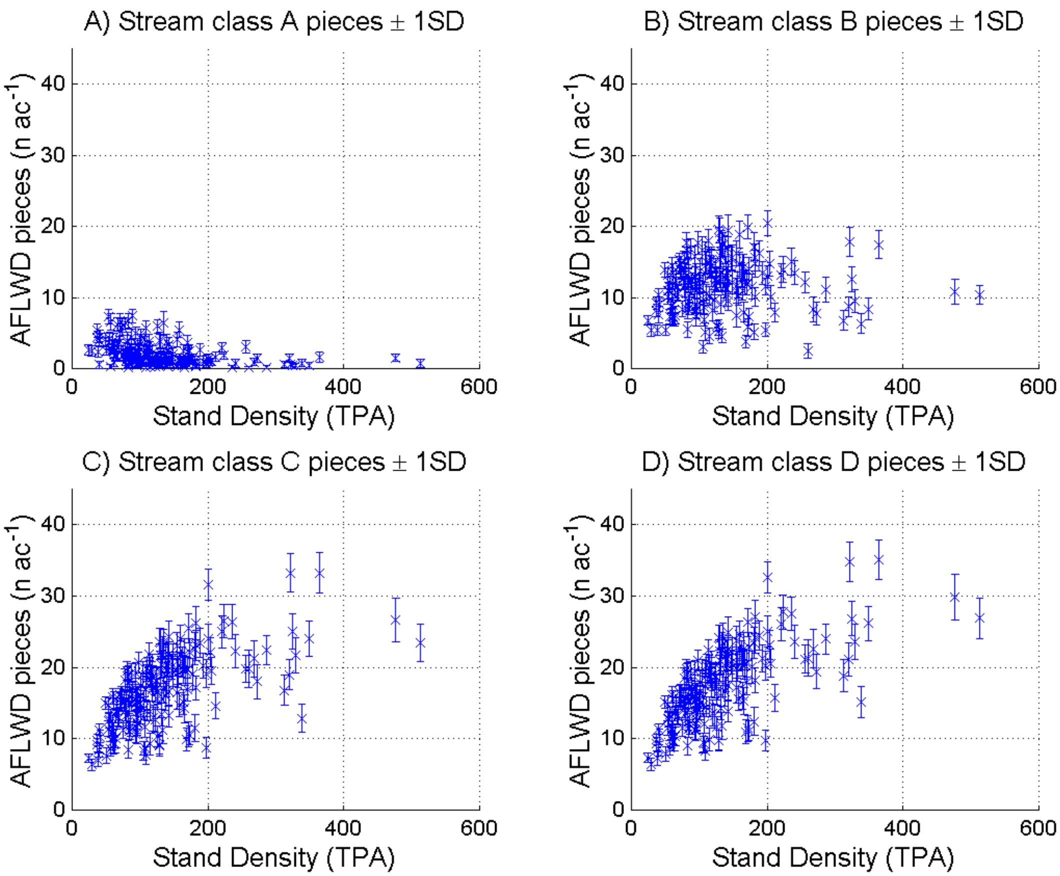

Figure 9: Expected values for potentially available functional LWD piece counts (pieces ac^{-1}) for each tree list T_l and stream classes A through D plotted against stand density. Values are means $\pm$ 1 std. dev. for one side of a stream, and were obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

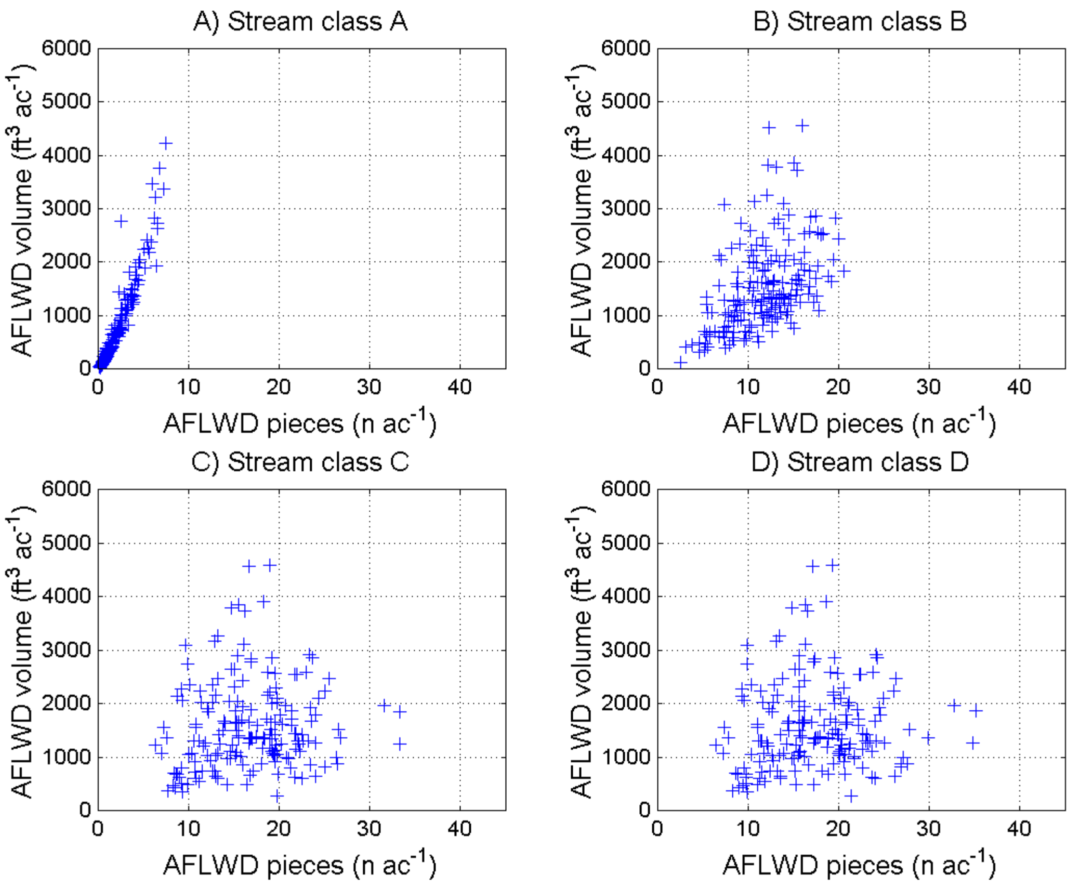

Figure 10: Scatter plots of mean expected values for potentially available functional LWD volume (ft^3ac^{-1}) and piece counts (pieces ac^{-1}) for each tree list T_l and stream classes A through D plotted. Values are means for one side of a stream obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

accumulation percent results are presented in Section 5.2.1, and the accumulation distance results are presented in Section 5.2.2.

5.2.1 Mean LWD accumulation percentages

Mean cumulative LWD profiles for volume and piece count, expressed as percent of total LWD, computed from the 129 available tree lists are shown in Figure 11 for stream classes A through D. The mean cumulative LWD profiles for stream classes E and F are indistinguishable from those of stream class D. Mean values and standard deviations for the cumulative percentages of potentially available functional LWD volume and piece count are presented in Table 6 and Table 7, respectively, for distances from a stream of 10 to 170 ft in 20 ft increments. Results for all six stream classes are presented in the tables.

Accumulation of LWD was most rapid for the largest streams, stream class A, indicated by the steeper slopes for the cumulative volume and piece count LWD profiles in Figure 11. Approximately 91.4% ± 8.6% of the LWD volume and 86.8% ± 13.2% of the LWD pieces were accumulated for stream class A by a distance from a stream of 50 ft, with the other stream classes having volume accumulations of approximately 79% ± 6.4% and piece count accumulations of approximately 66% ± 11% at that distance. At a distance from a stream of 90 ft, the volume and piece count accumulations for stream class A were approximately 98.9% ± 1.9% and 97.4% ± 4.4%, respectively, with volume accumulations for the other stream classes being approximately 96% ± 2.6% and piece count accumulations of approximately 90% ± 7% for stream classes B and C, with the remaining stream classes having accumulations of approximately 88% ± 7%. For all stream classes, LWD volume accumulated more rapidly than LWD piece count.

5.2.2 Mean LWD accumulation distances

Mean values and standard deviations for the distances from a stream where cumulative percentages of 100%, 99%, 95%, 90%, 85%, 80%, and 50% of the total potentially available functional LWD volume or piece count occurred for each tree list are presented in Table 8 and Table 9, respectively. These results complement the accumulation percent results, and values for all six stream classes are presented.

Distances at which fixed percentages of the accumulation of LWD volume and pieces were smaller for the larger stream size classes. Stream class A had 100% accumulation occurring within approximately 100.2 ± 41.4 ft of a stream for volume and 99.4 ± 42.2 ft of a stream for piece count. Distances from a stream for 100% of the LWD volume accumulation for the other stream classes ranged from 151.4 ± 19.2 ft for stream class B to 163.9 ± 10.9 ft for stream class F, and for piece count they ranged from 151.4 ± 19.9 ft for stream class B to 163.6 ± 11.8 ft for stream class F. Distances from a stream where 95% of the LWD volume

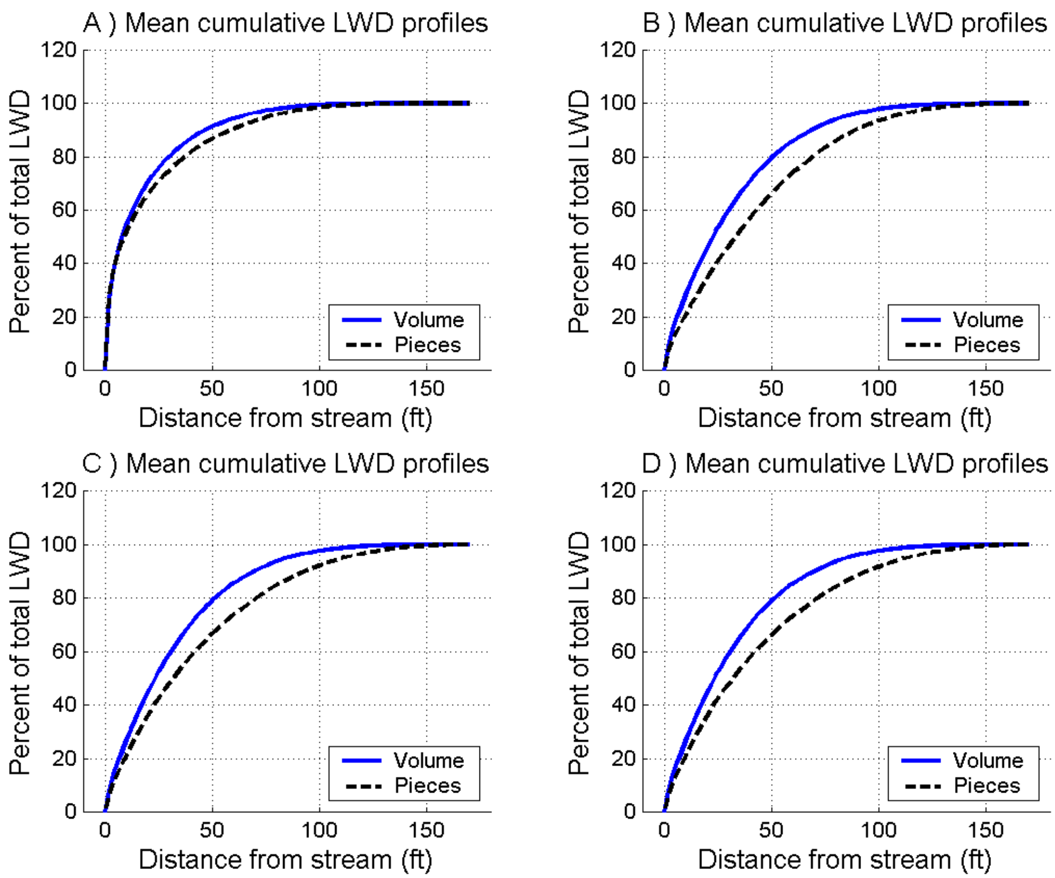

Figure 11: Mean cumulative profiles for expected potentially available functional LWD volume and piece counts as a percent of the total for stream classes A through D. Stream classes were averaged over the 179 available tree lists.

Table 6: Mean LWD volume accumulation, based on the percent of the total LWD volume produced by each tree list, for distances from a stream of 10 ft to 170 ft in 20 ft increments. Standard deviations are in parentheses. The average for each stream class was derived from all 129 available tree lists.

Distance from stream (ft)	Mean cumulative percent of volume (std. dev.) Stream Class					
	A	B	C	D	E	F
10.0	54.5	28.3	26.9	26.8	26.8	26.8
	(20.9)	(5.2)	(4.1)	(4.1)	(4.1)	(4.1)
30.0	80.2	60.0	59.1	59.0	58.9	58.9
	(14.6)	(7.3)	(6.8)	(6.8)	(6.8)	(6.8)
50.0	91.4	79.7	79.0	79.0	78.9	78.9
	(8.6)	(6.6)	(6.4)	(6.3)	(6.3)	(6.3)
70.0	96.5	90.5	90.1	90.0	90.0	90.0
	(4.5)	(4.7)	(4.6)	(4.6)	(4.6)	(4.6)
90.0	98.9	96.4	96.0	96.0	96.0	96.0
	(1.9)	(2.7)	(2.6)	(2.6)	(2.6)	(2.6)
110.0	99.7	98.8	98.6	98.6	98.6	98.6
	(0.7)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
130.0	100.0	99.7	99.6	99.6	99.6	99.6
	(0.2)	(0.4)	(0.5)	(0.5)	(0.5)	(0.5)
150.0	100.0	100.0	99.9	99.9	99.9	99.9
	(0.0)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
170.0	100.0	100.0	100.0	100.0	100.0	100.0
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)

Table 7: Mean LWD piece count accumulation, based on the percent of the total LWD pieces produced by each tree list, for distances from a stream of 10 ft to 170 ft in 20 ft increments. Standard deviations are in parentheses. The average for each stream class was derived from all 129 available tree lists.

Distance from stream (ft)	Mean cumulative percent of pieces (std. dev.) Stream Class					
	A	B	C	D	E	F
10.0	52.2 (23.5)	21.0 (7.3)	21.3 (7.0)	21.2 (7.0)	21.1 (7.0)	21.1 (7.0)
30.0	75.0 (18.9)	46.5 (9.9)	48.1 (11.3)	47.8 (11.3)	47.7 (11.3)	47.7 (11.3)
50.0	86.8 (13.2)	66.4 (10.5)	66.7 (11.1)	66.3 (11.1)	66.1 (11.1)	66.1 (11.1)
70.0	93.5 (8.3)	80.5 (9.5)	79.5 (9.4)	79.0 (9.3)	78.9 (9.3)	78.9 (9.3)
90.0	97.4 (4.4)	90.4 (7.0)	88.9 (7.0)	88.4 (7.0)	88.2 (6.9)	88.2 (6.9)
110.0	99.2 (1.9)	95.9 (4.3)	94.6 (4.6)	94.2 (4.6)	94.1 (4.6)	94.1 (4.6)
130.0	99.8 (0.6)	98.7 (1.9)	98.0 (2.4)	97.7 (2.4)	97.7 (2.5)	97.7 (2.5)
150.0	100.0 (0.2)	99.7 (0.5)	99.5 (0.8)	99.4 (0.8)	99.4 (0.8)	99.4 (0.8)
170.0	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)

Table 8: Mean distance from stream (feet) necessary to achieve LWD volume accumulations of 100%, 99%, 95%, 90%, 85%, 80%, and 50% of the total LWD volume produced by each tree list. Standard deviations are in parentheses. All stream classes were averaged over the 179 available tree lists. Values were based on one side of a stream.

LWD volume accumulation %	Mean distance (ft) from stream (std. dev.) Stream Class					
	A	B	C	D	E	F
100	100.2 (41.4)	151.4 (19.2)	161.2 (13.3)	163.1 (11.9)	163.9 (10.9)	163.9 (10.9)
99	72.1 (30.8)	107.0 (17.1)	110.5 (16.0)	110.9 (15.8)	111.0 (15.8)	111.0 (15.8)
95	53.7 (25.1)	82.6 (13.9)	84.2 (13.2)	84.4 (13.0)	84.4 (13.0)	84.4 (13.0)
90	42.9 (21.5)	68.4 (11.7)	69.4 (11.2)	69.6 (11.2)	69.6 (11.1)	69.6 (11.1)
85	35.7 (19.0)	58.8 (10.4)	59.6 (9.9)	59.8 (9.9)	59.8 (9.9)	59.8 (9.9)
80	30.3 (16.8)	51.2 (9.2)	52.0 (8.9)	52.1 (8.9)	52.1 (8.8)	52.1 (8.8)
50	11.5 (7.6)	23.2 (4.5)	23.9 (4.2)	24.0 (4.2)	24.0 (4.2)	24.0 (4.2)

accumulation occurred were 53.7 ± 25.1 ft for stream class A, 82.6 ± 13.9 ft for stream class B, and approximately 84.4 ± 13.0 ft for stream classes C through F. Distances from a stream where 95% of the LWD piece count accumulations occurred were 60.2 ± 31.2 ft for stream class A, 100.6 ± 19.8 ft for stream class B, and approximately 109 ± 19.5 ft for stream classes C through F. An LWD volume accumulation of 50% occurred at a distance of 11.5 ± 7.6 ft from a stream for stream class A, and within approximately 24.0 ± 4.2 ft from a stream for all other stream classes. The LWD piece count accumulation of 50% occurred at a distance of 14.3 ± 12.0 ft from a stream for stream class A, and within approximately 34.4 ± 9.3 ft from a stream for all other stream classes.

6 Discussion

Our objectives when developing and testing the individual tree based LWD availability simulation model were to produce a model that was in first order agreement with empirical studies and other models for LWD production or recruitment having similar assumptions. In section Section 6.1 we consider the agreement between mean expected values for po-

Table 9: Mean distance from stream (feet) necessary to achieve LWD piece count accumulations of 100%, 99%, 95%, 90%, 85%, 80%, and 50% of the total LWD pieces produced by each tree list. Standard deviations are in parentheses. All stream classes were averaged over the 179 available tree lists. Values were based on one side of a stream.

LWD piece accumulation %	Mean distance (ft) from stream (std. dev.) Stream Class					
	A	B	C	D	E	F
100	99.4 (42.2)	151.4 (19.9)	160.9 (14.2)	162.7 (12.8)	163.6 (11.8)	163.6 (11.8)
99	77.7 (35.5)	120.9 (20.9)	129.6 (20.2)	132.0 (19.5)	132.8 (19.4)	132.8 (19.4)
95	60.2 (31.2)	100.6 (19.8)	106.9 (19.9)	108.7 (19.6)	109.4 (19.5)	109.4 (19.5)
90	49.6 (28.3)	87.6 (18.3)	91.7 (18.6)	93.1 (18.5)	93.6 (18.5)	93.6 (18.5)
85	42.1 (25.7)	77.9 (16.8)	80.6 (17.4)	81.6 (17.2)	82.0 (17.2)	82.0 (17.2)
80	36.2 (23.6)	69.8 (15.3)	71.2 (16.0)	72.2 (16.0)	72.4 (16.0)	72.4 (16.0)
50	14.3 (12.0)	34.9 (8.4)	34.0 (9.2)	34.3 (9.2)	34.4 (9.3)	34.4 (9.3)

tentially available functional LWD volume and piece counts obtained from our model from empirical studies (Bilby and Ward, 1989, 1991, Fox, 2001, 2003), and other related issues. Next, in Section 6.2, we consider the cumulative profiles of potentially available functional LWD volume and piece counts perpendicular to a stream obtained from our model and their agreement with other similar models (McDade et al., 1990, Van Sickle and Gregory, 1990). We also consider possible implications of these results for riparian buffer management. Finally, in Section 6.3, we address some of the impacts of our simplifying assumptions on the LWD availability simulation model and identify several possible improvements.

6.1 Mean LWD volume and piece count

The potentially available functional LWD volumes and piece counts estimated by the LWD simulation model were in agreement with expectations. The estimated values for potentially available functional LWDvolumes and piece counts both increased as stream size, measured by bank-full width, decreased, approaching saturation points of approximately 1580.4 $\mathrm{ft}^3\mathrm{ac}^{-1}$ for volume and 17.6 pieces ac^{-1}. The saturation point must occur since the minimum dimensions for functional LWD logs are decreasing from a base diameter and length of 25.2 inches and 33.7 ft, respectively, for the largest stream size, stream class A, to the minimum dimensions for an LWD log, 4 inches and 6.6 ft, for the smallest stream size, stream class F. The results for stream classes A through C are consistent with the trends that have been reported from empirical studies of LWD in riparian areas for streams of different size (Bilby and Ward, 1989, 1991). The stream sizes for stream classes D through F are outside the range of those available from these empirical studies, precluding any comparisons.

The mean expected values for potentially available functional LWD volume and piece count rapidly increased to values near their respective saturation levels by stream class C, with stream classes D through F being essentially indistinguishable from one another. The primary reason for this effect was that the minimum dimensions for functional LWD were essentially the same for stream classes C through F. The base diameter values for these stream classes were 4.8, 4, 4, and 4 inches, with corresponding length values of 13.3, 8.4, 6.6, and 6.6 ft, respectively. The relatively small differences in the base diameter and length for these stream classes identified essentially the same potential functional LWD logs for all of the stream classes. The slightly greater functional length of stream class C provided the only differentiation among stream classes C through F.

The availability of LWD volume and pieces were influenced by both average tree size and stand density. This was clearly indicated by Figure 6 and Figure 7 for volume and by Figure 8 and Figure 9 for piece count. Lower values of potentially available functional LWD volume and number of pieces were produced by stands having dominant tree heights less than approximately 100 ft. Expected values for potentially available functional LWD volume were highly variable throughout the range of stand densities, and for small streams the range of volumes was nearly constant, with lower and upper bounds of 500 ft^3ac^{-1} and 3000 ft^3ac^{-1} for piece counts between 10 pieces ac^{-1} and 25 pieces ac^{-1}. Potential LWD volumes within this range are, then, produced by a broad range in the number of LWD pieces. To better understand the relationship between potentially available LWD volume and piece count requires an understanding of the stand structures that produce them.

As stand density increased, expected LWD volume initially increased and then decreased, while expected piece counts generally increased. These results may indicate a stand level size (height) threshold for the production of LWD for riparian forest stands, occurring near a dominant height of approximately 100 ft, and the existence of a trade-off between LWD volume and piece count. The existence of a size–density trade-off in potential LWD availability may be of particular importance for managed riparian areas. Values for potentially available LWD volume and piece count are coupled, or dependent, attributes. They are jointly dependent upon the stand density, tree locations, and size distribution of trees within a riparian stand. The largest potentially available LWD volumes do not occur for the largest potentially available piece counts, see Figure 10, but rather for intermediate piece counts, between 10 pieces ac^{-1} and 25 pieces ac^{-1}. This indicates that riparian stands containing a some large trees are necessary to obtain larger LWD volumes, and, therefore, that management to achieve piece count targets alone may not produce enough trees of sufficient size to obtain functioning instream LWD. The existence of a size threshold and a size–density trade-off are consistent with our understanding of stand dynamics and the fact that small trees, and trees far from a stream, cannot produce LWD logs having a size that is large enough to contribute significantly to expected LWD volume.

Stand structure, represented by the stand density and size distribution of the trees, and tree location relative to a stream, strongly influenced the amounts of potentially available LWD volume and piece counts. To provide some insight into the relationships among stand structure, tree location, and the potential for production of LWD, we selected seven sample stands based on their ALWD values, the AFLWD values small class E/F. Six of the seven stands, Stands 1 to 6, were selected to be representative the perimeter of the distribution, of ALWD volume and number of pieces, and the seventh was chosen to be near the center of the distribution, Stand 7. Summaries of the stand characteristics, and their mean ALWD values, are provided in Table 10, and plots of their ALWD values from the $N_S = 100$ simulation trials are shown in Figure 12. Of particular importance are the distributions of ALWD volumes and piece counts produced by each of the stands. Only the tree locations relative to a stream were changed for each stand to obtain the different ALWD values in the clusters of points. The locations and sizes of individual trees relative to a stream are critical for the potential production of LWD. For example, stands having some larger trees produced ALWD volumes having a range of approximately 2000 ft^3ac^{-1}, while stands having few or no larger trees produced volumes having a range of approximately 500 ft^3ac^{-1}. The range in the number of ALWD pieces also depended upon tree sizes, but was influenced by stand density as well, with stands having a mixture of tree sizes and higher densities producing

Table 10: Stand attributes and simulated potentially available LWD volumes and piece counts for seven sample stands, see Figure 12.

Stand	TPA	QMD (in)	H (ft)	Total BA (ft^2ac^{-1})	Total volume (ft^3ac^{-1})	ALWD pieces ($n\ ac^{-1}$)	ALWD volume (ft^3ac^{-1})
1	476.7	11.3	52.3	331.3	11916.6	30.9	1364.1
2	312.7	11.6	50.1	230.0	7697.0	19.6	673.1
3	128.2	24.1	124.5	404.9	23513.5	24.4	2863.0
4	128.9	13.0	63.0	118.9	5336.2	10.0	500.7
5	63.4	22.0	86.0	167.9	8597.8	9.7	2062.5
6	70.2	29.4	148.2	330.7	22655.9	16.7	3725.2
7	164.2	17.5	75.7	275.0	14425.4	16.3	1637.4

the broadest ranges in number of ALWD pieces, stands 1 and 2.

The three stands having smaller average tree sizes, stands 1, 2, and 4, define the lower boundary of the ALWD volume and piece count distribution, and stands having larger tree sizes, stands 3, 5, and 6, define the upper boundary of the distribution. Stands 3 and 4 have almost identical stand densities but different size distributions, and correspondingly different potential to produce LWD. In fact, they appear on opposite sides of the ALWD volume and piece count distribution. The highest density stand, stand 1, produced a distribution of ALWD volumes and piece counts that were intermediate in value, but stand 2, having a lower stand density but nearly equal average tree size produced noticeably less ALWD. The reason for this becomes clear when we look at the total basal area and total volume values for these stand: stand 1 has some larger trees as indicated by its much greater total basal area and volume. Stands 5 and 6 have the lowest densities but larger average tree sizes. Stand 5 produces an intermediate ALWD volume values and a lower ALWD piece count values, while stand 6, produces the largest ALWD volume values and intermediate ALWD piece count values, while having only 10 more TPA, nearly all of which appear to contribute to the ALWD piece count.

Finally, if we assume that there exists some form of regional equilibrium between the potentially available functional LWD in riparian areas and the LWD that has actually been recruited into streams as functional LWD, which seems reasonable, we may make a direct comparison of our results with those reported in empirical studies of instream LWD Bilby and Ward (1989), Fox (2001). Differences in the way volumes were computed, by our simulation model and the two empirical studies, precludes a comparison of LWD volume values, so we proceed with a comparison based only on piece counts. To perform the LWD piece count comparison, we standardized the values to a 328.1 ft reach of stream and counted both sides. We applied a scale factor of $2 \cdot (328.1/256.2) = 2 \cdot 1.28 = 2.56$, to convert the piece count

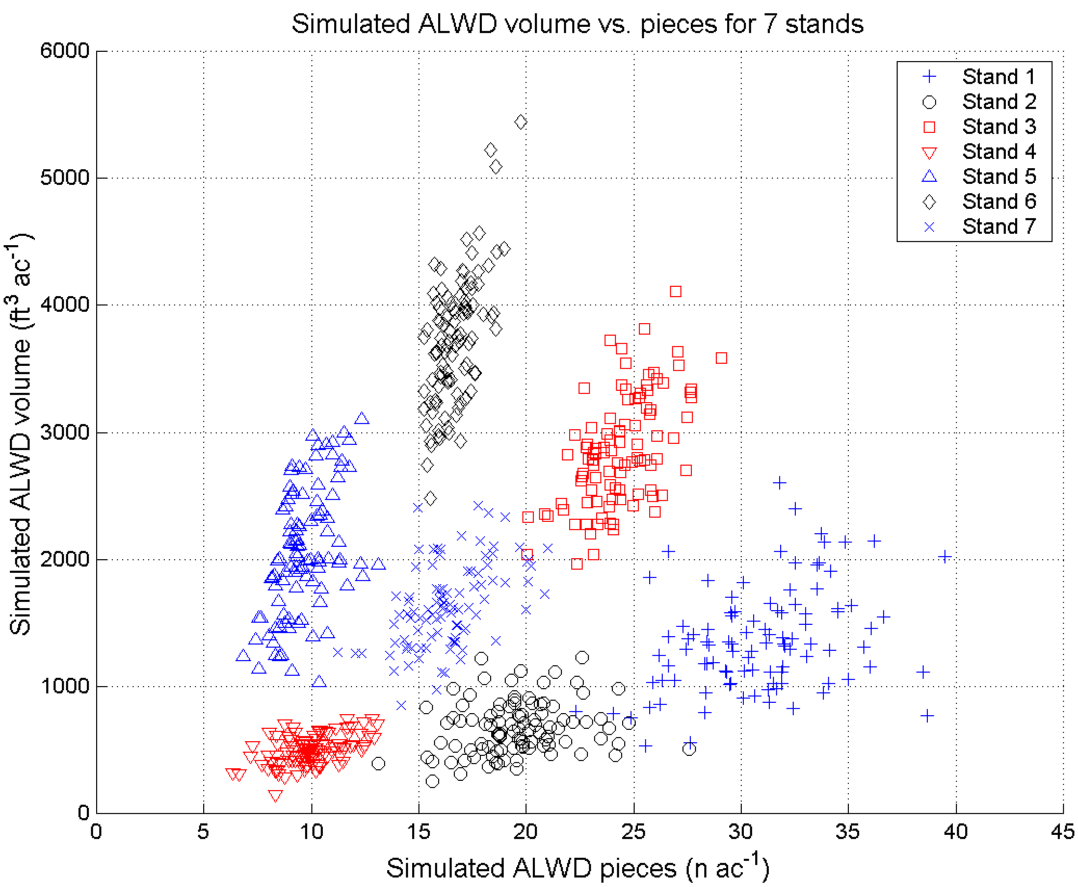

Figure 12: Simulated potentially available LWD volumes and piece counts for 7 stands. The points for each stand represent the values from each of the $N_S = 100$ simulation trials from which the mean values for each stand were obtained.

Table 11: Estimated potentially available functional LWD pieces per 328.1 ft of stream reach.

Stream Class	W_j^{bf} (ft)	Mean	Std. Dev.	Q25	Median	Q75	Range
A	75.5	5.5	4.3	2.2	3.9	7.8	18.7
B	33.1	30.0	9.7	22.6	30.4	36.6	46.2
C	13.5	42.7	13.4	32.5	42.0	50.6	68.9
D	8.5	44.5	14.1	33.6	43.5	53.3	73.3
E	5.2	45.0	14.4	33.8	43.7	53.9	75.2
F	3.3	45.0	14.4	33.8	43.7	53.9	75.2

values for our one acre riparian buffer with a stream reach of 256.3 ft into equivalent values for the 328.1 ft stream reach and both sides of a stream. Means and standard deviations for the standardized expected AFLWD piece count values appear in Table 11, along with their medians, their 25% and 75% quartiles, and their ranges.

Potentially available functional LWD piece counts for larger streams,stream classes A, B, and C, were compared to values derived from an empirical relationship,given in Equation 57, relating the mean number of functional LWD pieces per meter of stream reach, $N_{\mathrm{fun}}^{\mathrm{lwd}}$, to the bank-full width, W^{bf}, in meters, for streams in for western Washington Bilby and Ward (1989).

$$\text{functional pieces per meter} = 10^{-1.12*\log_{10}(W^{\mathrm{bf}})+0.46} \tag{57}$$

The data used to estimate the empirical relationship had a minimum bank-full width of 13.1 ft and the maximum observed bank-full width value used to estimate the relationship was 65.6 ft. Given the form of the equation, which increases without bound as the bank-full width approaches zero, we could not use it to predict piece count values for our small streams, for which we expect the mean piece count to saturate at some finite value. Our largest stream class exceeded the maximum value observed in the data, but we felt that extrapolating to larger streams was acceptable. Values predicted by the empirical relationship in Bilby and Ward (1989) for a 328.1 ft reach of stream are given in Table 12 for stream classes A through C. Observed values for the frequencies of functional LWD were quite variable, relative to the fitted curve, so in addition to estimates of the mean values obtained from Equation 57, we also visually estimated upper and lower bounds for observed functional LWD frequencies from Figure 2 in Bilby and Ward (1989) for our stream classes using nearby points to provide an additional frame of reference for the results.

The magnitudes of the mean expected values for the potentially available functional LWD piece counts for the three largest stream classes obtained from our LWD simulation model were in good agreement with those predicted from Bilby and Ward (1989). The simulation model may underestimate the mean number of functional LWD pieces relative to values from Bilby and Ward (1989) for stream class A, where values of 5.5 and 8.6 pieces per 328.1 ft, respectively, were obtained. An approximate range for this stream size class was from 6

Table 12: Estimated functional LWD piece counts for 328.1 ft of stream reach. The values were obtained from the empirical equation relating the mean number of pieces per unit of stream reach to the bank-full width from Bilby and Ward (1989).

Stream Class	W^{bf} (ft)	Mean Pieces	Lower Bound	Upper Bound
A	75.5	8.6	6.0	10.0
B	33.1	21.6	12.0	41.0
C	13.5	59.4	34.0	69.0

Table 13: Observed total LWD pieces per 328.1 ft of stream reach as reported in Fox (2001).

W^{bf} (ft)	Mean	Std. Dev.	Q25	Median	Q75	Range	N
0.0-19.7	32.5	15.6	25.5	29.0	37.9	67.5	19
19.7-98.4	52.0	33.0	29.2	52.3	63.4	131.7	49

to 10 pieces, and the value of 5.5 obtained from the simulation model is close to the lower bound, and may, therefore, be reasonable. For stream class B, the simulation model appears to over predict the mean number of functional LWD pieces relative to the mean value from Bilby and Ward (1989), giving a value of 30.0 pieces *vs.* a mean of 21.6 pieces per 328.1 ft. The value of 30.0 pieces produced by the simulation model is, however, well within the range of observed values for this stream size, given by the approximate bounds of 12.0 pieces to 41.0 pieces. For stream class C, we obtained values of 42.7 and 59.4 functional LWD pieces per 328.1 ft, respectively, from the simulation model and Equation 57, indicating that the simulation model may underestimate the number of functional LWD pieces for streams of this size. Again, however, the value of 42.7 produced by the simulation model is well within the range of observed values for this stream size, which ranged from 34.0 pieces to 69.0 pieces.

For the small streams, stream classes D, E, and F, we used total LWD piece count values for western Washington streams from Fox (2001, 2003) for comparison. The total piece counts were based on a minimum LWD piece size having a diameter of 3.9 inches and a length of 6.6 ft and LWD piece count values for stream classes with bank full widths from 0 ft to 19.7 ft and 19.7 ft to 98.4 ft were reported by Fox and used here for comparison with the simulated potentially available LWD piece counts. We considered both of these stream classes from Fox because results for the smaller stream class were based on only 19 sample points, which may not have been sufficient to characterize the distribution of LWD piece counts for small streams. In addition to means and variances, Fox also provided median values, 25% and 75% quartiles, and ranges for the total LWD piece counts.

The magnitudes of the mean expected values for the potentially available total LWD piece counts for the smallest stream classes obtained from our LWD simulation model were consistent with results from Fox (2001). We obtained a mean value of 45.0 pieces per 328.1 ft of stream reach for stream class F, with Fox reporting mean values of 32.5 pieces for small stream sizes and 52.0 pieces for intermediate stream sizes, which bracket our estimated value. Similar relationships hold for the median and quartiles. Fox reported values of 29.0, 25.5, and 37.9 for the median, 25% and 75% quartiles, respectively, for the number of LWD pieces for the small stream sizes, and values of 52.3, 29.2, and 63.4 for the number LWD pieces in the intermediate stream size class. We obtained values of 43.7, 33.8, and 53.9, for the median and quartiles, respectively, from the simulation model.

These results indicate that our simulation model may overestimate the mean number of LWD pieces for small streams and that it may underestimate the mean number of LWD pieces for intermediate stream sizes. Before drawing this conclusion, we must consider two factors. First is the age distribution of stands sampled in Fox (2001, 2003). The mean values for the total number of LWD pieces in Fox (2001, 2003) were computed from stands having an age range from less than 150 years to over 800 years with the majority of stands having ages in the rang of 200 to 500 years, Figure 17 in Fox (2001). The age range for the stands used to obtain the simulated values was 100 to 180 years, with a mean value of approximately 120 years. Differences in the stand ages between Fox (2001, 2003) and the data set used as the basis for our simulation may be influencing the results. In fact, Fox reports that the number of LWD pieces recruited into a stream over the first 150 years is, on average, larger than the number of LWD pieces recruited into streams for the subsequent 400 years, after which the value rises again. Thus our selection of stands within the stem exclusion and stand differentiation stages (Oliver and Larson, 1996) may be inflating our LWD piece count values, relative to a natural, long term, background level. From Figure 18 B in Fox (2003), the mean number of LWD pieces per 328.1 ft of stream reach for stands having ages less than 150 years was approximately 50, while for stands having ages in the range 150 years to 550 years the mean value was approximately 35. If we reduce our simulated LWD piece counts by a factor of $35/50 = 0.70$ to bring them into alignment with the values for the bulk of the data in Fox (2001, 2003), we get values of 31.5 for the mean number of pieces, with a median of 30.6, quartiles of 23.7 and 37.7, and a range of 52.6, all values that are in much better agreement with those reported in Fox (2001) for western Washington.

Second, larger streams will transport more LWD, possibly even creating more pieces due to breakage during transport, than smaller streams. This could lead to large accumulations of LWD in jams or along stream banks. Transport of LWD logs within a stream is not included in our simulation model, and this seems to be the most likely candidate for factors contributing to the underestimation of the mean number of pieces for the intermediate stream class of Fox (2001, 2003). Further investigation into this issue is necessary to determine if this is indeed the cause of the underestimation, but that is beyond the scope of this work, whose intent was to demonstrate general agreement with the results of empirical studies which has been shown.

6.2 Mean cumulative LWD profiles

The cumulative LWD profiles produced using the LWD availability simulation model are in general agreement with results reported by McDade et al. (1990) and Van Sickle and Gregory (1990). The definitions used for LWD logs in these studies were compatible with those chosen for our potential LWD logs, so we may only compare these results to those for the smaller stream classes, which estimate the total abundance of LWD. McDade et al. (1990) reported values for LWD piece counts only, and gave empirical results indicating that approximately 70% of LWD piece accumulation occurred within 65 ft of a stream for mature or old-growth conifer forests in the Oregon and Washington, and model estimates indicating that approximately 85% of LWD piece accumulation occurred within 98.4 ft. Van Sickle and Gregory (1990) reported model estimates for both LWD volume and piece count. They considered two types of stands: a uniform height stand with all trees having a height of 164.0 ft, and a mixed height stand with tree heights ranging from 65 ft to 213.3 ft in height. Their results for LWD volume for the mixed height stand indicated that approximately 95% of the volume and 90% of the pieces occurred within a distance of 65 ft of a stream, and that for the uniform height stand approximately 90% of the volume occurred within a distance of 65 ft, but only approximately 60% of the pieces. These values are in good overall agreement with those obtained for the smallest stream size, stream class F, which had cumulative LWD volume and piece count percentages of approximately 90.0%±4.6% and 78.9%±9.3%, respectively, at a distance from a stream of 70 ft.

The mean cumulative profile results for potentially available functional LWD identified three LWD availability characteristics that may have an impact on riparian buffer design. All three characteristics are related to the idea of an effective buffer width for a stream. There are any number of ways that the effective buffer width for a stream could be defined. We chose to define the effective buffer width based on the likelihood that a tree could fall and produce a functional LWD log, that is, the effective buffer width is the distance perpendicular to a stream delineating the region of the forested buffer adjacent to a stream reach that is most likely to produce a functional LWD log for that stream.

First, larger streams have narrower effective buffer widths, on average, than smaller streams. This is true whether we consider potentially available functional LWD volume or piece counts. The narrower effective buffer width is a direct result of the fact functional LWD logs are larger, on average, for larger streams, and that trees must be closer to a stream to produce LWD logs that would be large enough to be functional for those streams. Large streams, therefore, require large trees near them to potentially produce functional LWD logs.

Second, there is a point of diminishing returns for LWD volume and piece counts that occurs as the buffer width is increased. That is, the marginal gain in potentially available functional LWD volume or pieces is small relative to the change in buffer width. For example, to move from a 90% LWD volume accumulation level to a 99% LWD volume accumulation level requires an additional buffer width of 29.2 ft for stream class A and an additional buffer width of approximately 41.4 ft for stream classes D, E, and F, while the first 50% of the LWD volume accumulation occurred within 11.5 ft of the stream for stream class A and within, approximately, 24.0 ft of the stream for stream classes D, E, and F. Results for piece count accumulation were similar, requiring an additional buffer width of 28.1 ft for stream class A and an additional buffer width of approximately 39.2 ft for stream classes D, E, and F, while the first 50% of the LWD volume accumulation occurred within 14.3 ft of the stream for stream class A and within, approximately, 34.4 ft of the stream for stream classes D, E, and F. Clearly, trees that are located closer to a stream are more important for the potential production of LWD than trees that are farther from a stream, and the costs of adding an additional marginal amount of LWD must be considered.

Third, potentially available functional LWD volume accumulates more rapidly than potentially available functional LWD pieces. For example, the mean distances from a stream for a 90% accumulation of LWD volume and pieces were 42.9±25.1 ft and 49.6±28.3 ft, respectively, for stream class A, with a mean difference of 6.7 ft, and 69.6±11.1 ft and 93.6±18.5 ft, for stream classes D, E, and F, with a mean difference of 24.0 ft. This implies that the potentially available LWD pieces occurring furthest from a stream are not contributing significantly to the potentially available LWD volume. If the size, measured by volume, of functional LWD logs was more important than their number, then the logs produced by trees further from a stream may not be relevant. There may, therefore, be a trade-off between the quality and quantity of functional LWD logs.

If such a volume–piece count trade-off exists, where functional LWD volume is more important than the number of pieces, the trade-off could be used to define an effective buffer width based on both piece count and volume. First the level of volume accumulation desired would be chosen. This would then define a mean distance from a stream for each stream size class. Next, the mean distance would be used to obtain the piece count accumulation level. For example, a 90% LWD volume accumulation level would occur at a distance from a stream of 42.9 ft for stream class A and 69.6 ft for stream classes D, E, and F, giving piece count accumulation levels of approximately 85% or the potentially available pieces for stream class A and 80% of them for stream classes D, E, and F.

6.3 Impacts of model assumptions

We made a number of simplifying assumptions when implementing the simulation model for estimating expected values for potentially available LWD. These simplifications made have a direct impact on the results produced by the model. We now consider several of the most important assumptions and discuss some of their individual impacts on the results.

6.3.1 Tree fall directions

We assumed that tree fall directions θ were uniformly distributed in the interval $[-\pi, \pi]$. This implies that the local physical environment of a tree does not influence its fall direction, and, therefore, that trees fall independently of one another. The probability of stream intersection for a tree is clearly affected by its local physical environment. To improve the LWD availability simulation model a better characterization of the tree fall direction probability distribution that takes into account some of the factors from the local physical environment is necessary. For example, a tree that has other trees between it and a stream, potentially obstructing its fall toward the stream, will be less likely to intersect the stream if it falls than a tree the same distance away having no potentially obstructing trees. The simulation model therefore overpredicts the LWD volume or piece counts that may potentially be available for tree locations further from a stream, which also increases the effective buffer width. When a better tree fall direction distribution becomes available it may be incorporated into the simulation model. The assumption of uniformly distributed tree fall directions was consistent with what others have done (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002), and facilitated comparisons with their work.

6.3.2 The dimensions of stream intersecting logs

The point of stream intersection was used as the point of reference for defining the dimensions of a stream intersecting log for two reasons. First, using the point of stream intersection ties the log dimensions and position directly to a stream, providing a consistent point of reference for all stream intersecting logs. Second, the length and midpoint diameter of stream intersecting logs, the measurements that have typically been reported (Bilby and Ward, 1989, 1991, Fox, 2001), do not permit a complete specification of the position of a stream intersecting log, relative to the stream it intersects. In particular, the point of stream intersection on a log cannot be identified from the midpoint diameter and length. Further, the portion of a stream intersecting log that remains on the stream bank can vary tremendously depending on the size and distance to the stream of the tree that fell to produce it. So, in the absence of additional measurements that would allow a more complete description of the position and characteristics of a stream intersecting log relative to a stream, the point of stream intersection was used as the base an LWD log. As more information about the distributions of LWD log dimensions, locations relative to a stream, and number of pieces created from each tree become available, this portion of the model could be modified by incorporating the additional information. The size and volume of LWD logs is directly affected by this assumption, since the portion of the LWD log on the stream bank was not included. Our methods, however, were consistent with what others have done (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002), and may be modified to improve the quantitative agreement of the model with empirical results.

6.3.3 LWD volume and piece count estimates

The assumption of a perpendicular tree fall direction when computing the dimensions and volume of an LWD log may cause both LWD volume and piece counts to be overestimated. We performed an experiment where the perpendicular tree fall direction assumption, $\theta = 0$ for all trees, was modified to incorporate uniformly distributed tree fall directions for $\theta \in [-\alpha, \alpha]$. This change to the tree fall direction assumption caused a reduction in the average expected LWD volume values of approximately 29% for stream class A, 24% for stream classes B and C, and 23% for stream classes D, E and F. The LWD piece count average values were also reduced, by approximately 26% for stream class A, 16% for stream class B, 10% for stream class C, 7% for stream class D, and 6% for stream classes E and F. Using a perpendicular tree fall direction for all trees maximizes both the LWD volume and piece count for a particular stand configuration. These results indicate that the expected LWD volume values may be quite sensitive to the tree fall direction, which is not surprising since changes in the tree fall direction can significantly reduce the dimensions of potential LWD logs, subsequently reducing their volumes. Expected LWD piece counts are somewhat less sensitive, except for stream class A, where changes in the fall direction reduce the log dimensions, subsequently causing logs that qualified as functional LWD for a perpendicular fall direction to fail to qualify for a nonperpendicular fall direction.

If the expected LWD volume and piece count values obtained here were to be used to support the determination minimum levels of LWD for use in practice, the fact that the perpendicular tree fall direction maximizes the LWD volume and piece count values would need to be taken into account. In this context, computed LWD volumes and piece counts would be conservative, that is larger than expected, and limits should be set accordingly. Alternatively, now that it is implemented, new results based on the random tree fall could be computed and used to guide the determination of minimum levels of potentially available LWD. So long as the same computational procedures are used to obtain estimates of potentially available LWD, relative comparisons among results from different sources or from different applications may be performed.

6.3.4 Tree distribution

We assumed that the distribution of perpendicular distances of trees from a stream f_{distance} was uniform within the 170 ft width of the riparian buffer. The specific shape of this distribution is not known, but an approximation to it could be derived empirically given the requisite data. The possible shapes for this distribution are bracketed by distributions that are skewed toward the stream, having the majority of trees located further from the stream, and by distributions that are skewed away from the stream, having the majority of trees located nearer to the stream, with the uniform distribution being the neutral distribution in the middle of the possible shapes. If the distribution of tree distances from a stream is skewed toward the stream, the assumed uniform distribution would overestimate potentially available functional LWD volume and piece counts, since it would locate more trees near the stream. A distribution of perpendicular tree distances that was skewed away from a stream, having more trees closer to the stream and its water than further away, would seem to be more beneficial to tree survival, and in this situation the uniform distribution would underestimate potentially available functional LWD volume and piece counts. The assumption of uniformly distributed perpendicular distances from a stream is only an approximation, but it is consistent with what others have done (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) and facilitates the comparison of results. This distribution may be modified once a better understanding of this distribution is obtained, or to use a mixture distribution for different species when such a distribution becomes available.

6.3.5 Tree list expansion and rounding of TPA values

When we expanded our sample tree lists to obtain tree lists where each tree represented exactly one tree per acre, we simply rounded the individual TPA values for each tree, and assigning a value of one to trees having TPA values that rounded down to zero. The rounding errors caused by applying this simple rule for expanding the tree list may not compensate, that is, the amounts that were rounded up may not be approximately equal to the amounts that were rounded down, and hence they may not cancel out. There are two potential sources for the rounding errors to accumulate, causing an increase or decrease in the number of TPA used to estimate the LWD values and subsequent changes to the size distribution of the trees within a tree list. First, rounding up, or down, a number of trees from a fixed size plot where all of the trees have equal TPA values, e.g., rounding 1.25 down to 1.0 for all trees on a 0.80 acreplot, or rounding 2.51 up to 3.0 for all trees on a 0.40 acre plot. Second, rounding TPA values from variable radius plots to zero and assigning them a value of one may could introduce a bias due to the fact that large trees have smaller TPA values for this type of sample. Error accumulations similar to those for fixed size plots are also possible for variable radius plots, where multiple trees get rounded down, or up, reducing or increasing the number of trees and their size distribution to estimate the LWD values.

Since the use of this simple rounding rule could affect the number and size distribution of trees represented by a tree list, which, in turn, could affect the estimated values for LWD volumes and pieces, we performed a straightforward comparison of the actual stand attributes for the 179 sample plots with the stand attributes computed using the expanded tree lists obtained from the simple TPA rounding rule. Mean values, standard deviations, and results from Kolmogorov-Smirnov (K-S) goodness of fit tests (Bickel and Docksum, 1977, Zar, 1996) comparing the distributions of stand density, QMD, average height, total basal area, and total volume for the actual tree lists with the expanded tree lists are presented in Table 14. We used the K-S test because we were interested in differences between the distributions of each of the stand attributes computed using the actual TPA values and the expanded

Table 14: Comparison of the actual stand attribute values, computed using fractional trees, and values computed using the expanded tree lists where each tree represented exactly one tree, obtained using a simple TPA rounding rule. The K-S test was performed for an $\alpha = 0.05$, with $n = 179$, giving a critical value of $d_{\text{crit}} = 0.1005$.

Attribute	Actual Mean (Std. Dev.)	Expanded Mean (Std. Dev.)	d_{obs}	R^2
Stand density (TPA)	134.6 (77.8)	132.6 (77.1)	0.0670	0.9973
QMD(in)	20.3 (5.3)	21.0 (6.0)	0.0782	0.9604
Height (ft)	98.9 (26.3)	99.6 (27.1)	0.0391	0.9881
Total basal area (ft^2ac^{-1})	256.0 (68.6)	268.1 (84.5)	0.0838	0.7352
Total volume (ft^3ac^{-1})	12767.6 (4112.8)	13641.5 (5276.4)	0.0950	0.7456

TPAvalues, and not simply difference between mean values. A nonparametric test was also warranted here because most of these attribute distributions were not symmetric. The K-S test was performed for an $\alpha = 0.05$, with $n = 179$, giving a critical value of $d_{\text{crit}} = 0.1005$. Also provided in the table are R^2 values for each of the attributes computed using all of the sample plots.

Differences in mean values for the attributes, actual tree list minus expanded tree list, were 1.96 TPA for stand density, -0.6 inches for QMD, -0.7 ft for average tree height, -12.1 ft^2ac^{-1} for total basal area, and -874.0 ft^3ac^{-1} for total volume. Attribute values computed from the expanded tree list are all well within one standard deviation of the actual mean values, and represent, relative to the actual mean values, a decrease of 1.5% in stand density, and increases of 3.0%, 0.6%, 4.7%, and 6.8% for the remaining attributes, respectively.

The R^2 values obtained by comparing the attributes for the actual and expanded tree lists were 0.9973 for stand density, 0.9604 for QMD, 0.9881 for average height, 0.7352 for total basal area, and 0.7456 for total volume. These R^2 values indicate very strong linear relationships for stand density, QMD, and average height, and indicate strong, but more variable, relationships for total basal area and total volume.

These results are consistent with the rounding procedure causing more larger trees to be included in the tree lists, inflating the average tree size, total basal area, and total volume values. We know that this is indeed the case for trees whose actual TPA values were rounded down to zero; they were larger trees, relative to the other trees on their respective plots. The reduced R^2 values for total basal area and total volume also indicate that the variability of these attributes has increased somewhat, relative to the actual values for these attributes. The standard deviations for these attributes computed from the expanded tree lists are greater than those computed from the actual tree lists, indicating that they do have greater variability.

At this point, we know that there are differences between the attribute values computed from the actual tree lists and the expanded tree lists. The rounding procedure may have introduced a bias toward larger trees being included. What we need to ascertain is whether that potential bias introduces differences in the distributions of the attributes values that may be sufficient to impact the expected values computed for the LWD volumes and piece counts. The results of the K-S goodness of fit test did not find any statistically significant differences between distributions of the attribute values computed from the actual tree lists and the attribute values computed from the expanded tree lists. Given these results, the expected LWD volume and piece count values computed from the actual tree lists are expected to be similar to those computed from the expanded tree lists; the lack of significant differences in the attribute value distributions implies that the actual tree lists and the expanded tree lists may, essentially, be treated as equivalent samples.

While the rounding procedure may have introduced a small bias toward larger expected LWD volumes and piece counts, this may be considered to hedge against producing values that are too small, making the LWD estimates conservative for applications where lower bounds are being determined. We are considering two other alternatives for tree list expansion. The first is to expand the tree lists in a way that includes trees having fractional TPA values as independent trees that get placed relative to a stream in the same manner as the "whole" trees. The expected value formulas work for this case too. The second alternative is to add an addition layer into the LWD simulation model that selects trees based on the probabilities of occurrence in a sample. The probabilities of occurrence would be obtained from the TPA values associated with each tree in a sample. In this manner we can always have whole trees, but still represent the distribution of trees within the sampled stand. This alternative could also be implemented in a way permit the stand density to vary within the simulation as well, since we know that stand density varies from location to location, even within "uniform" stands.

7 Conclusions

An individual tree based simulation model for estimating the expected value of potentially available instream LWD was developed and tested. The model emphasized the distributions of characteristics that directly affect the potential availability of instream LWD, in particular the probability of stream intersection, the distribution of tree fall directions, and the distribution of distances from the stream for trees in a riparian forests. The LWD availability simulation model was designed in a modular manner, allowing the substitution of alternative distributions, either to incorporate localized information or to adjust the characteristics of the model based on alternative distributions, for increased flexibility. The model described may easily be used with the tree list output from forest growth and yield models or forest stand simulators.

The simulation model for potentially available LWD was used to estimate mean, regional expected values for functional LWD volume and piece counts for western Washington. The trends in mean functional LWD volume and piece count produced by the simulation model decreased as stream size increased, a response that was in agreement with acknowledged trends for functional LWD. The distributions of the expected mean values for potentially available functional LWD volumes and piece counts were both skewed toward larger values, indicating that smaller values were more likely to occur than larger values. The potentially available functional LWD volumes and piece counts also had a high degree of variability relative to their mean values. A critical implication for management would be that small values for potentially available functional LWD may be more typical than larger values, and that they should, therefore, not be arbitrarily excluded from consideration in managed riparian areas by setting high minimum LWD levels as targets for management, e.g., using a mean or median value as a lower bound for acceptance.

Cumulative profiles for potentially available functional LWD volume produced by the model increased more rapidly than those for LWD piece count. If LWD volume was more important than the number of pieces, then there may exist a trade-off between the LWD volume and the number of LWD pieces. A similar trade-off may exist between the quality, e.g., size, and quantity of LWD pieces. If smaller functional LWD pieces were of lower quality than larger functional LWD pieces, then LWD produced from trees far from a stream would be less important. These types of trade-offs could have a significant impact on the widths of riparian buffers that are deemed necessary to achieve desired levels of instream LWD, particularly for small streams.

The effective buffer width, the buffer width necessary to deliver a particular proportion of the total potentially available functional LWD into a stream, is generally much smaller than the buffer width defined by a site-potential tree height. Using our examples, the effective buffer width for obtaining 90% of the potentially available functional LWD volume for a small stream is approximately 69.6 ft, but a site potential tree height based buffer width is 170 ft, which is almost 2.5 times wider. This is of particular importance, since the costs to landowners of wider riparian buffers may be large while providing only marginal gains in potential stream benefit. While wider buffers may be afford other benefits to a stream they may not be warranted on the basis of the potential for the production of instream LWD.

The level of detail necessary to support forest management decisions and the determination of forest policy continues to increase. As the level of detail necessary to make decisions or set policy has increased, so has the importance of recognizing the inherent variability in a forest stand, or other natural system, whether managed or not. The models used to support forest management decisions or policy must be constantly improved to meet the demands for increased detail and to provide estimates of the inherent variability. Simulation models, such as the one described here for potentially available LWD, provide one means for simultaneously meeting the demand for greater detail and estimates of the inherent variability. Distributional assumptions in this type of simulation model may be easily changed as more information is obtained, for example, a better understanding of the distribution of perpendicular tree distances from a stream or the distribution of tree fall directions, becomes available, by simply modifying the input distribution used to represent the particular aspect of the model. Simulation models may, therefore, provide an effective, flexible tool for the support of forest management and forest policy decisions.

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