Potentially available LWD metrics for assessing riparian forest function

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Abstract

Models for in stream large woody debris are typically ecologically oriented, past looking, and cumulative, incorporating myriad highly variable input and output processes to estimate amount of large woody debris. Including these processes, while important from an ecological perspective, may not be an effective strategy from management or regulatory perspectives, as their inclusion introduces modeling uncertainties, and subsequently, management or regulatory uncertainties. Assuming that the current and future states are of primary importance within management and regulatory contexts and that in stream large woody debris originates within forests adjacent to streams, an individual tree bootstrap simulation system supporting multi-zone riparian forest management was developed and used to compute a distribution of metrics for potentially available large woody debris. The metrics are demonstrated by identifying a reference condition and then assessing several riparian management scenarios. Finally, the potentially available large woody debris metrics are shown to be equivalent to a class of ecologically oriented models that are in active use.

Key Words: Large woody debris, bootstrap simulation, riparian forest management

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. These roles include, but are not limited to, bank stability, shade, 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, Beechie and Sibley, 1997, Beechie et al., 2000, Bragg, 2000, Bragg et al., 2000, Fox, 2001, Welty et al., 2002, Benda et al., 2003, Benda and Sias, 2003, Fox, 2003, Gregory et al., 2003, Meleason et al., 2003, Hassan et al., 2005). 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 in Washington State since the listing of salmon and other anadromous fish species in the Pacific Northwest as threatened under the Endangered Species Act and the subsequent passage of the Forests and Fish Law (WFPB, 2001).

Given the importance of in stream LWD to stream function, and its role in the creation of potential fish habitat, a number of models have been developed to estimate expected LWD contributions to a stream from the adjacent forests, as well as providing estimates of some of the characteristics, e.g., size and location, of LWD logs that may be produced (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Bragg, 2000, Bragg et al., 2000, Welty et al., 2002, Benda et al., 2003, Benda and Sias, 2003, Gregory et al., 2003, Meleason et al., 2003, Hassan et al., 2005). The majority of LWD models are ecologically oriented, past looking, and cumulative, attempting to account for myriad highly variable input and output processes including mortality, wind, landslides, transport and breakage within a stream, scouring, and decomposition to estimate amounts of LWD present in a stream at a particular location and point in time. The modeling of these processes, while important from an ecological perspective, may not be the most effective strategy for use of these models from management or regulatory perspectives, since their inclusion introduces modeling uncertainties and additional complexity, and subsequently management or regulatory uncertainties and complexity.

There is significant potential for conflict between the past looking, understanding and knowledge oriented ecological perspective and the present and future looking, control and compliance oriented management and regulatory perspective. This conflict can far too easily lead to unwanted complexities from either perspective, for example extremely detailed analyses and tools with hundreds of parameters describing a riparian forest or the introduction of arbitrary complexity into forest management rules through negotiation and compromise. Ecological and management and regulatory conflicts resolved through negotiation and compromise can also lead to oversimplifications, that reduce the effective use of the ecological understanding and the effectiveness of rules established to sustainably use, conserve, restore, or protect a natural ecosystem. For example, choosing an easy to compute, but poorly correlated surrogate such as basal area per acre (BAPA), as was done in the Forests and Fish Law, instead of an attribute that is more relevant but difficult to compute or use, or combination of attributes, such as estimates of potential LWD abundance and volume or shade, to assess riparian forest function and potential benefit to a stream.

Conflicts between the ecological and management and regulatory perspectives can be resolved, or greatly reduced, by a thorough and careful consideration of the desired objectives, current scientific understanding, and available tools, and a recognition that within the management and regulatory contexts the full complexity of ecological models or assessment tools may not be necessary. Simplifications to the ecological models and tools may be used where appropriate, provided sufficient care is taken to avoid oversimplification, e.g., the use of single attributes when multiple attributes are necessary or the use of single value assessment rules where distribution based assessment rules are better suited. The choice of relevant attributes for the regulatory and management models and tools being developed for a particular situation is also important, as is the recognition that the attributes used in the management and regulatory process may not be identical to those used for the ecological models and tools. The underlying issues are fundamentally ecological in nature, and there must be sufficient information included within the management and regulatory process to make informed decisions that are relevant, implementable, and correct, to the extent possible, while maintaining the ecological integrity.

1.1 The Forests and Fish Law of Washington State

With the listing of salmon and other anadromous fish species in the Pacific Northwest as threatened under the Endangered Species Act, Washington State passed its Forests and Fish Law in 1999 and the Washington State Forest Practices Board adopted permanent rules implementing the Forests and Fish protection measures in 2001. The primary objectives of the Forests and Fish Law are to: (1) provide compliance with the Endangered Species Act for aquatic and riparian-dependent species; (2) restore and maintain riparian habitat to support a harvestable supply of fish; (3) meet the requirements of the Clean Water Act for water quality; and (4) keep the timber industry economically viable in the state of Washington. These objectives are to be achieved through management practices that create or retain forest stands that will develop characteristics similar to mature, unmanaged, conifer dominated or mixed riparian stands when they reach an age of 140 years. An adaptive management monitoring program was also established to provide feedback on the effectiveness of the implemented Forests and Fish rules, and to allow modifications to the rules as necessary based upon accumulated scientific evidence. The Forests and Fish rules are different for eastern and western Washington due to their different biogeographic characteristics, and only the rules for western Washington are considered here.

The Forests and Fish rules specify a riparian management zone (RMZ) on each side of potentially fish bearing streams having a total width based on the site potential tree height or site class for Douglas-fir (*Pseudotsuga menziesii*). Each RMZ is then subdivided into three subzones parallel to a stream. The first subzone, adjacent to a stream, is the *core zone*, and it is a 50 foot wide no harvest zone. The second subzone, the *inner zone*, where limited harvest may be permitted subject to leave tree, shade, and other constraints. The third subzone, the *outer zone*, where harvest is permitted subject to leave tree and other constraints. The widths of the inner and outer zones vary depending on Douglas-fir site class and stream size. Two stream size classes are used: streams < 10 feet in bankfull width and streams ≥ 10 feet in bankfull width.

Assessments to determine whether any inner zone harvest is permitted under the

Forests and Fish rules are performed in two steps. First, the current forest conditions are projected to an age of 140 years using a forest growth model. Second, the basal area per acre (BAPA) for the combined core and inner zones is compared to a threshold at 140 years. If the BAPA value is less than the threshold, then no inner zone harvest is permitted. If the BAPA value is greater than or equal to the threshold, then inner zone harvest is permitted subject to shade and other constraints, provided the residual trees allow the combined core and inner zone BAPA value to meet or exceed the threshold when projected to 140 years.

The Forests and Fish rules provide two leave tree options, Option 1 and Option 2 for inner zone harvest when permitted and outer zone harvest. Under Option 1, the inner zone harvest must be from below and at least 57 conifer trees per acre (TPA) with diameter at breast height (DBH) values of at least 12 inches, or the largest diameter trees must be left in the harvested area. Outer zone harvest under Option 1 must leave 20 conifer TPA with DBH values of at least 12 inches. The number of leave trees in the outer zone may be reduced, on a basal area for basal area basis, by placing large woody debris in a stream or by tallying trees within channel migration zones. Trees designated as leave trees under Option 1 are required to be left uncut in all future harvests.

Under Option 2, the simpler option, the no harvest zone adjacent to the stream is extended from the core zone into the inner zone for an additional 30 feet for streams < 10 feet in bankfull width and 50 feet for streams ≥ 10 feet in bankfull width. In addition, trees furthest from the stream must be removed first, leaving 20 conifer TPA having DBH values of at least 12 inches, or the largest diameter trees in the harvested area. Outer zone harvest under Option 2 must leave 20 conifer TPA with DBH values of at least 12 inches. The number of leave trees in the outer zone may, however, be reduced to a minimum of 10 TPA if the combined core and inner zones have a projected BAPA surplus at age 140 on a basal area for basal area basis. Trees designated as leave trees under Option 2 are required to be left uncut in all future harvests.

The BAPA thresholds are referred to as the desired future condition (DFC) target. The initial DFC BAPA targets were site class dependent, based on Douglas-fir site classes, and were negotiated based on a "found" data set pieced together from several sources. The initial DFC BAPA targets were: 285 $\text{ft}^2\text{ac}^{-1}$, 275 $\text{ft}^2\text{ac}^{-1}$, 258 $\text{ft}^2\text{ac}^{-1}$, 224 $\text{ft}^2\text{ac}^{-1}$, and 190 $\text{ft}^2\text{ac}^{-1}$, respectively, for Douglas-fir site classes I – V. These values were assumed to be interim values, to be used until a data set representative of 140 year old, unmanaged, conifer dominated and mixed riparian forests in western Washington could be collected and used to validate the DFC BAPA targets or identify alternative DFC targets. Such a data set, the desired future conditions validation data set (DFCVDS), was collected and analyzed (Schuett-Hames et al., 2005). Based on an analysis of this data set, a new, one-size-fits-all (OSFA) BAPA value of 325 $\text{ft}^2\text{ac}^{-1}$ was established as the new DFC target for all site classes in the Fall of 2009.

Given the complexity of the Forests and Fish rules, a DFC model was developed to provide an easy to use tool to perform the projections to an age of 140 years and the necessary BAPA computations and assessments. The DFC model consists of thousands of growth model runs for a wide variety of initial stand conditions and thinning treatments that have been converted into lookup tables for interpolation. Users of the DFC model input the necessary information, including the locations of trees relative to a stream, tree sizes, species, and other information, and the model provides as output information describing the potential for harvest in the inner zone, leave tree requirements for the inner and outer zones, estimates of surplus BAPA and various other details related to the stand projection and assessment.

This section was intended to provide only a brief overview of the Forests and Fish Law of Washington State and the specific rules related to the quantitative management targets and assessment procedures developed for basal area per acre at 140 years. More complete descriptions of the Forests and Fish Law can be found at the following web sites.

`http://www.forestsandfish.com`
This is the main web portal for information about the Forests and Fish Law in Washington State.

`http://apps.leg.wa.gov/WAC/default.aspx?cite=222`
The Washington Forest Practices rules, published in Title 222 of the The Washington Administrative Code.

`http://apps.leg.wa.gov/RCW/default.aspx?cite=76.09`
The Washington Forest Practices Act, Chapter 76.09 of the Revised Code of Washington.

1.2 Objectives

The use of BAPA within the Forests and Fish Law of Washington State as a primary component of the DFC target to assess riparian forest function begs the question of whether BAPA is an adequate ecological surrogate to more direct measures of riparian forest function, e.g., estimates of large woody debris or shade. Further, as this brief introduction has demonstrated, the Forests and Fish rules are quite complex and come with a set of models and tools to be used for assessment of management scenarios using BAPA and other criteria.

Using the Forests and Fish Law of Washington State as a convenient backdrop, the primary objective is to demonstrate a relevant simplification of ecologically oriented models for in stream LWD that meets the temporal requirements of management and regulatory perspectives, that maintains the necessary ecological integrity, and that can be used to develop straightforward, easy to use models and tools. The relevant simplification is to focus on the forest as the source of in stream LWD and not the stream as a complex, dynamic container for LWD. The potential *availability* of LWD from the forest, then, becomes the central idea, rather than the potential *recruitment* of LWD into a stream and its subsequent dynamics.

A simulation model to estimate potentially available functional LWD (AFLWD) was developed (Gehringer, 2008a,b). The basis of the AFLWD simulation model is the individual trees, their sizes and locations relative to a stream, the most relevant attributes for riparian function, as well as being the entities that are managed. The AFLWD simulation model was used to compute metrics of potentially available LWD volume and pieces, as well as estimates of their distribution, for riparian forests in western Washington State. The expected values for the AFLWD volume and piece count were computed for several stream or log size classes. Estimates of AFLWD volume and piece count source distance profiles were also computed to determine the most likely source distances from a stream for potential LWD recruitment.

Finally, the AFLWD model results are compared to the OSU Streamwood model (Meleason et al., 2003), an ecological model of in stream LWD dynamics, to show that there was no loss of ecological integrity by demonstrating the equivalence between the AFLWD metrics and the output of the OSU Streamwood model.

2 Methods

2.1 Computing the potentially available LWD metrics

The simulation model for computing the potentially available LWD metrics makes three basic assumptions. First, live, standing trees in forests adjacent to streams are the primary source of in stream LWD. Second, individual tree sizes and locations relative to a stream are the most important characteristics influencing the probability of stream intersection and the production of a piece of LWD. Third, functional LWD log dimensions vary by stream size, with larger streams requiring larger LWD logs. Think of this as log "stickiness."

The AFLWD simulation model requires as input one or more tree lists containing diameter at breast height (DBH), height, TPA and species information, a distribution of tree fall directions, the size of the modeled riparian area, minimum dimensions for functional LWD logs, equations for computing log dimensions and volumes, and the number of bootstrap simulation trials to be performed. The tree lists may be actual tree lists or output from a forest growth model. Tree locations may also be provided, but locations are generated by the simulation model to estimate the distribution of the AFLWD metrics. The distribution of tree fall directions was assumed to be uniform, so trees could fall in any direction. The modeled area represented a one acre riparian forest stand on one side of a stream having a width, measured perpendicular to the stream, of 170 feet and a straight stream reach, measured along the stream, of 256.2 feet. Minimum dimensions of functional LWD logs for five stream size classes are provided in Table 1. The different stream classes provide a size breakdown for the AFLWD logs. The AFLWD volume and piece count values for stream class A, representing the largest streams, tally the largest AFLWD logs, with values for stream class B tallying all AFLWD logs for both A and B streams, etc., until all potential LWD logs are tallied for stream class E. The values from stream class E are assumed to represent to total AFLWD values. Approximate distributions of values for the AFLWD metrics were obtained for each tree list as well as for western Washington using 100 bootstrap trials that randomly selected and placed trees within the simulated RMZ.

Given all of the inputs to the AFLWD simulation model, the AFLWD metrics are computed in the following steps for each tree list representing a riparian stand.

Step 1 Expand the tree list into individual trees having TPA values less than or equal to one by replicating each tree having a TPA value greater than one and including any remainder. This provides an expanded tree list, allowing each tree to represent itself in the subsequent computations.

Step 2 Randomly (uniformly) assign each tree in the expanded tree list a location within the modeled area. See Figure 1 for an example of randomly generated tree locations.

Table 1: Minimum functional LWD log base diameters and lengths for five 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).

Stream class	Bank-full width (ft)	Minimum LWD base diam. (in)	Minimum LWD length (ft)
A	75.0	25.6	44.0
B	30.0	10.3	24.5
C	15.0	5.3	15.0
D	7.5	4.0	7.5
E	5.0	4.0	6.6

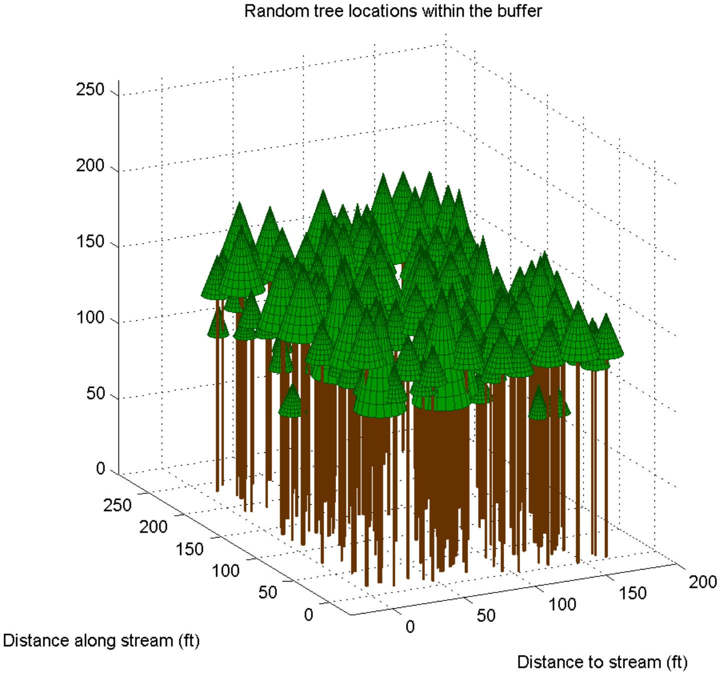

Figure 1: Example of randomly generated tree locations and an expanded tree list.

Step 3 Compute the effective tree height and the limiting stream intersection angle α. The effective height of a tree is the height to a four inch upper stem diameter. The limiting stream intersection angle is the angle between the perpendicular line from the tree to the stream and the upstream radius of the circle having a radius equal to the effective tree height, centered on the tree, that makes the stream bank a chord of the circle. See Figure 2 for an example showing the effective tree height and the limiting stream intersection angle α

Step 4 Compute the probability of stream intersection for each tree. Assuming a uniform fall direction distribution implies that the probability of stream intersection is $\alpha/180$.

Step 5 Assign a stream intersecting fall direction to each tree. Trees are assumed to fall independently. For a random (uniform) fall direction, choose a uniformly distributed random value in the interval $(-\alpha, \alpha)$. For perpendicular fall directions, assign a value of zero.

Step 6 Compute the dimensions and volume of the stream intersecting logs using the point of near bank stream intersection as the base of the log. The top of the log is given by the effective height. Figure 3 provides an example of the log computations for a tree falling perpendicularly toward a stream.

Step 7 Compute the expected AFLWD contribution for each tree using the probability of stream intersection. The expected AFLWD volume for each tree is obtained by multiplying the volume of a stream intersecting log by the probability of stream intersection. The expected value for the AFLWD count for each tree is simply the probability of stream intersection.

Step 8 Sum the expected values filtering by the minimum dimensions for each size class to compute the number of AFLWD pieces and the AFLWD volume for each of the stream/log size classes.

Step 9 Repeat steps 1-8 the desired number of times and compute the desired statistics or distributions.

2.2 Reference data set description

The reference data set selection was motivated by the approach used to sample the DFCVDS (Schuett-Hames et al., 2005). The data collection objective for the DFCVDS data was to "collect data on stand characteristics from a random sample of mature [140 year old], unmanaged conifer and mixed composition riparian stands in western Washington" (Schuett-Hames et al., 2005) that were representative of areas managed under the Forests and Fish rules. The DFCVDS reference data consists of 113 sample plots with a targeted map-based age range of 120 to 140 years and a field verified age range from 80 years to over 200 years. The majority of sampled plots were in the Cascade and Coast Mountain Ranges, 98 plots, with the remainder in the Puget Sound lowlands. Plots were selectively filtered by rejecting potential sample plots having less than 30% canopy closure and plots having "unsuitable stand age or composition, or conditions unsuitable for tree growth," such as, "rock outcrops,

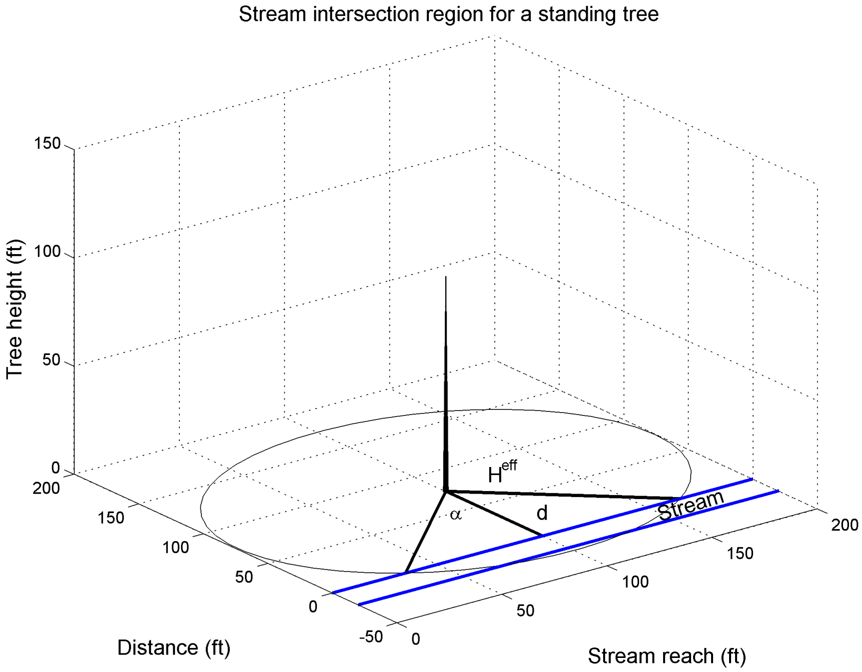

Figure 2: Example showing the effective tree height and the limiting stream intersection angle α.

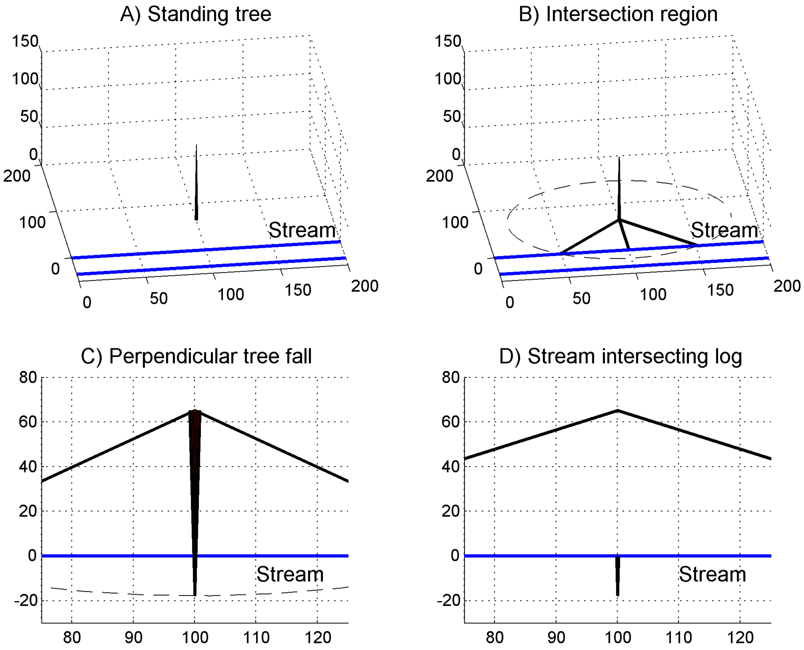

Figure 3: Example of the AFLWD log computations for a tree falling perpendicularly toward a stream.

talus slopes, landslide scarps or standing water," among other criteria (Schuett-Hames et al., 2005). This *selectivity* has the potential to introduce a selection bias toward forest stands having greater stocking levels, i.e., stands having greater numbers and sizes of trees relative to average or typical stand conditions.

The reference data set is used to compute regional estimates of AFLWD for western Washington, and was derived from the PNW-FIA Integrated Database version 2.0 (Hiserote and Waddell, 2004) to mimic the stated objectives for the DFCVDS, but to emphasize Douglas-fir dominant and mixed stands, which are among the dominant managed forest types in western Washington. This data set will be referred to as the FIAREF reference data. A total of 553 plots were selected from the FIA-IDB version 2.0 for the FIAREF data. The plots selected were classified as timberland with an FIA forest type of Douglas-fir, had at least 50% of their BAPA represented by Douglas-fir, and had ages in the range from 100 to 180 years, and were from Oregon and Washington west of the Cascade Mountains. The FIA-IDB sample plots are on a regular grid throughout the region, and should, therefore, provide a consistent sample of the forest structures distributed throughout the region. Two issues, however, do arise when using plots from the FIA-IDB.

First, using only information contained within FIA-IDB version 2.0, it is not possible to definitively determine whether a particular plot has had some sort of harvest activity. It is, however, possible to obtain plot notes from the inventory surveys directly from the FIA for review. Two steps were taken to address this issue: (1) plots identified as having trees associated with a residual overstory were removed to reduce the potential impact of plots that may have been subject to some harvest activity; and (2) field notes for site classes I, II, and III were available from a different project and were used to definitively identify a subset of unmanaged plots for comparison to the overall FIAREF data set.

Second, and again using only information contained within FIA-IDB version 2.0, it is not possible to determine whether plots were riparian plots located near a stream. If, however, stands are selected based on dominant species and site quality, as was done here for the FIAREF data, issues relating to whether a stand is riparian or not become moot: riparian and upland stands having the same dominant species and site class are assumed to have, on average, the same level of productivity and similar stand structure.

Gross forest structure attributes are being used, e.g., TPA, QMD, and BAPA, and estimates of LWD, and the natural variability of these attributes is large, so the use of stands from the FIA-IDB that have not been definitively determined to be unmanaged and riparian is expected to have minimal impact on the results. Gross forest structures are determined by the number and sizes of the trees and snags, and coarse woody debris within a forest stand, with finer levels of detail obtained by including tree species information if necessary. The number and sizes of the trees present in a well defined area adjacent to a stream are sufficient to obtain a good estimate for the production of LWD, and the gross forest structures within riparian stands adjacent to small streams were assumed to be similar to those in upland, or nonriparian, stands dominated by the same species.

Given this assumption, the range in forest structures for riparian stands with small streams would be well represented by the range in structures for upland or nonriparian stands, and estimates of AFLWD derived from the upland stands would provide estimates of AFLWD values consistent with those that would be obtained from 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 larger streams should, therefore, also be acceptable. Finally, there is 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 of upland stands to estimate LWD characteristics for riparian stands. When selecting data to define the reference condition for the simulations, no distinctions were made between data from upland and riparian stands.

To lend support to this statement, the TPA and QMD values for the the FIAREF reference data and a known to be unmanaged subset of the FIAREF data set for site classes I, II, and III (FIAREFU) are plotted in Figure 4. Note in particular that the two data sets have a large region of overlap within which the distributions of their points are very similar. Also notice that the FIAREF data set has more points to the left and below the overlap region. This may be explained by the inclusion of site classes IV and V in the FIAREF data set, relative to the FIAREFU data set. The less productive site classes would be expected to appear below and to the left of the more productive site classes. From this examination of the data sets, there is no compelling reason to disqualify the FIAREF data as being representative of unmanaged forest conditions within riparian areas.

2.3 Management scenario descriptions

Five management options were used to develop five multi-zone management scenarios that are compared to highlight some of the features of the AFLWD simulation model. A 160 year time horizon was used when running the forest growth model projections for compatibility with the time horizon of the Forests and Fish Law. This time horizon was deemed sufficient for comparisons within the context of the law, while providing an indication of the initial post 140 year trajectories for the management scenarios. The forest growth model used was SMC-ORGANON version 8.2, an updated version of the SMC-ORGANON model (Hann et al., 1997, Hanus et al., 1999, Hann et al., 2003, 2006) calibrated using the forest inventory database of the Stand Management Cooperative (Chappell et al., 1988). The SMC-ORGANON forest growth model was used here since the DFC model within the Forests and Fish rules also used the SMC-ORGANON model, version 6.0.

Tree lists for each of the management options described below were based on the SMC-ORGANON model projections with five year output intervals using an initial tree list representing an actual, 20 year old riparian stand, the base stand. The base stand is a 100% pure stand of Douglas-fir, that contained 471 standing, live Douglas-fir trees per acre, located in south-western Washington State. The base stand had a site index of 120 ft at 50 years and was a Douglas-fir site class II stand (King, 1966). The trees in the base stand had a mean DBH of 7.4 inches, with a standard deviation of 1.9 inches and a range from 4.0 inches to 13.0 inches, a mean height of 48.5 ft, with a standard deviation of 3.9 ft and a range from 43.0 ft to 67.0 ft. This stand structure was considered to be representative of the young, relatively dense riparian forest stands that dominate the managed riparian areas in western Washington, and was chosen as the base stand for the management option projections for this reason. All of the management options were assumed to represent a one acre riparian buffer area with Douglas-fir site class II and a 50 year site index of 120 ft (King, 1966). The SMC-ORGANON model projections were performed using internal height and diameter growth calibrations that adjust the model to the account for the initial tree dimensions, site index, and age. No other model calibrations were performed.

The management option descriptions appear in the list below. In the management option descriptions a commercial thinning is denoted by CT and represents a thinning operation producing sufficient merchantable material to at least offset the cost of the thinning operation. Two types of thinning operations are used: thinning from below and proportional thinning. Thinning from below removes the smallest diameter trees first and proportional thinning removes trees equally from all diameter classes. For each management option the complete set of management operations over the 160 year time horizon are included.

NOACTION Plant 471 TPA and grow with no thinning.

UPLAND Plant 471 TPA. CT to 180 TPA from below at age 20. CT to 100 TPA from below at age 35. Clearcut at age 50, leaving 2 TPA at least 20 inches DBH and another 2 TPA at least 12 inches DBH. Plant 300 TPA. CT to 180 TPA from below at age 70. CT to 100 TPA from below at age 85. Clearcut at age 100, leaving the 4 largest TPA. Plant 300 TPA. CT to 180 TPA from below at age 120. CT to 100 TPA from below at age 135. Clearcut at age 150, leaving the four largest TPA. Plant 300 TPA.

UNDERPLANT Plant 471 TPA. Commercial thin to 180 TPA from below by DBH at age 20. Commercial thin to 100 TPA from below by DBH at age 35. Commercial thin to 60 TPA from below by DBH at age 50. Commercial thin to 48 TPA proportionally by DBH at age 60. Commercial thin to 41 TPA proportionally by DBH at age 70. Commercial thin to 25 TPA from below by DBH at age 70 and underplant with 150 TPA Douglas-fir and 150 TPA western red cedar (*Thuja plicata*). Commercial thin to 180 TPA from below by DBH at age 100. Commercial thin to 120 TPA from below by DBH at age 120. After age 120, no further thinning.

10LEAVE Plant 471 TPA. CT to 180 TPA from below at age 20. CT to 100 TPA from below at age 35. Clearcut at age 50, leaving 10 TPAat least 12 inches DBH. Plant 300 TPA. CT overstory to 8 TPA proportionally at age 60. CT overstory to 7 TPA proportionally at age 70. CT to 180 TPA from below at age 70. CT to 100 TPA from below at age 85. Clearcut at age 100, leaving 10 TPA at least 12 inches DBH. Plant 300 TPA. CT overstory to 8 TPA proportionally at age 110. CT overstory to 7 TPA proportionally at age 120. CT to 180 TPA from below at age 120. CT to 100 TPA from below at age 135. Clearcut at age 150, leaving 10 TPA at least 12 inches DBH. Plant 300 TPA. CT overstory to 8 TPA proportionally at age 160.

20LEAVE Plant 471 TPA. CT to 180 TPA from below at age 20. CT to 100 TPA from below at age 35. Clearcut at age 50, leaving 20 TPA at least 12 inches DBH. Plant 300 TPA. CT overstory to 16 TPA proportionally at age 60. CT overstory to 14 TPA proportionally at age 70. CT to 180 TPA from below at age 70. CT to 100 TPA from below at age 85. Clearcut at age 100, leaving 20 TPA at least 12 inches DBH. Plant 300 TPAĊT overstory to 16 TPA proportionally at age 110. CT overstory to 14 TPA proportionally at age 120. CT to 180 TPA from below at age 120. CT to 100 TPA from below at age 135. Clearcut at age 150, leaving 20 TPA at least 12 inches DBH. Plant 300 TPA. CT overstory to 16 TPA proportionally at age 160.

Descriptions of the five management scenarios, their respective management zones, and the assigned management options appear in the list below. The management scenarios were generated using a multi-zone managed riparian buffer simulation system (Gehringer, 2008b) that uses bootstrap simulations (Efron, 1982, Efron and Tibshirani, 1998) to approximate distributions of stand attributes for each management scenario and output year using the management option tree lists generated by a forest growth model. The bootstrap simulations randomly selected and placed trees within a riparian management subzone proportionally using tree lists from the management option assigned to that subzone. All of the management scenarios were assumed to represent a one acre riparian buffer area having a width, measured perpendicular or upslope to a stream, of 170 ft, the total buffer width required by the the Forests and Fish Law for Douglas-fir site class II, and a reach along a stream of 256.2 ft. All management scenarios were assumed to represent stands with Douglas-fir site class II and a 50 year site index of 120 ft (King, 1966). A random, uniform, distribution of tree locations was assumed within each defined management zone, and only trees having diameter at breast height values of at least four inches were used.

50 ft No Harvest This management scenario represents the baseline 50 foot no harvest zone required by the Forests and Fish rules and has two subzones. The first subzone is assigned the NOACTION management option and ranges from 0 ft to 50 ft from a stream. The second subzone is assigned the UPLAND management option and ranges from 50 ft to 170 ft from a stream.

Bio-pathway This management scenario represents a biological pathway (Carey et al., 1999) intended to produce a mixed species, Douglas-fir and western red cedar, forests with multiple canopy layers and has three subzones. The first subzone is assigned the NOACTION management option and ranges from 0 ft to 25 ft from a stream. The second subzone is assigned the UNDERPLANT management option and ranges from 25 ft to 80 ft from a stream. The third subzone is assigned the UPLAND management option and ranges from 80 ft to 170 ft from a stream.

FF Option 2 $\geq$ 10 ft This management scenario approximates the Forests and Fish rules for streams greater than ten feet wide under Option 2 and has three subzones. The first subzone is assigned the NOACTION management option and ranges from 0 ft to 100 ft from a stream. The second subzone is assigned the 20LEAVE management option and ranges from 100 ft to 120 ft from a stream. The third subzone is assigned the 10LEAVE management option and ranges from 120 ft to 170 ft from a stream.

FF Option 2 $<$ 10 ft This management scenario approximates the Forests and Fish rules for streams less than ten feet wide under Option 2 and has three subzones. The first subzone is assigned the NOACTION management option and ranges from 0 ft to 80 ft from a stream. The second subzone is assigned the 20LEAVE management option and ranges from 80 ft to 114 ft from a stream. The third subzone is assigned the 10LEAVE management option and ranges from 114 ft to 170 ft from a stream.

No Action This management scenario represents the no action baseline of an unmanaged forest and has a single zone, which is assigned the NOACTION management option from 0 ft to 170 ft.

The astute reader will at this point have noticed two minor discrepancies between the Forests and Fish management scenarios FF Option 2 $\geq$ 10 ft and FF Option 2 $<$ 10 ft, just described, and the previous description of the rules for the Forests and Fish management Option 2. First, the 20LEAVE and the 10LEAVE management options permit the harvesting of some of the leave trees, 6 of 20 TPA and 3 of 10 TPA, respectively. The decision to allow harvest of some of the leave trees in these scenarios was made for economic reasons, specifically, to help offset the cost of the commercial thinning operations. Second, the thinnings were from below, since the ORGANON forest growth model is not spatially explicit and cannot represent tree locations. Given the distances of these trees from a stream, at least 100 ft for FF Option 2 $\geq$ 10 ft and 80 ft for FF Option 2 $<$ 10 ft, the removal of the leave trees should have limited impact on the stream. The lack of tree locations for the thinnings has no impact on the required basal area computations. Aside from the harvest of the leave trees and the lack of tree locations, the FF Option 2 $\geq$ 10 ft and FF Option 2 $<$ 10 ft management scenarios are consistent with riparian forest management required for Option 2 under the Forests and Fish rules.

Trajectories for the AFLWD piece count and volume metrics were generated for each of the five management scenarios and assessed relative to a 90% acceptance region obtained from the joint distribution of the AFLWD metrics using approximate probability contours (Gehringer, 2006). The AFLWD metrics for stream/log size class E were used for the assessment as an approximation to total available functional LWD. Before performing the assessments, the AFLWD metrics were scaled to represent both sides with of a 328.1 foot reach of stream to facilitate comparisons with OSU Streamwood.

2.4 OSU Streamwood comparison

The direct comparison between the AFLWD metrics and OSU Streamwood is possible since the two models use almost identical assumptions for key elements in their designs, including the use of a bootstrap simulation, tree placement within a riparian buffer, tree fall and stream intersection geometry, and the use of a random (uniform) tree fall direction distribution. The differences between the approaches, however, are what need to be addressed to make an effective comparison. The primary differences between the AFLWD metrics model and OSU Streamwood are that (1) OSU Streamwood simulations are for recruited in stream LWD; (2) OSU Streamwood assumes that only mortality trees can contribute to LWD and that they do so the year they die; (3) OSU Streamwood includes transport, breakage, and decay, and therefore has requires a depletion rate; (4) OSU Streamwood integrates or sums the input and output processes over time; and (5) OSU Streamwood uses a forest gap growth model. The second, third, and fourth differences are those that need to be addressed to make the AFLWD metrics comparison with OSU Streamwood.

For the comparison of the AFLWD piece count and volume metrics with the OSU Streamwood LWD model (Meleason et al., 2003), only the No Action management scenario is considered. This comparison demonstrates the equivalence of the AFLWD metrics and the OSU Streamwood in stream LWD model for unmanaged forests. Making comparisons for other management scenarios is feasible, but more complicated, and is unnecessary since the unmanaged forest condition defines the baseline for all other types of comparisons. For the comparison to AFLWD, OSU Streamwood was configured to simulate a 170 foot wide RMZ and to use random, uniformly distributed tree fall directions. The version of the OSU Streamwood model used for the comparisons was the 12-21-2001 release.

The AFLWD metrics were converted to be compatible with OSU Streamwood in four steps. First, compute the mortality percentages between the five year output times for the No Action management scenario. Second, multiply the AFLWD values by the mortality percentages to convert them to a mortality basis. Third, account for the dynamic losses by assuming a loss of 60 cubic feet of volume every five years (12 cubic feet of volume per year) and 3 LWD pieces every five years (0.6 pieces per year), and subtracting the losses from the mortality based AFLWD values to obtain depleted AFLWD values. Values to use for the depletion were difficult to find and OSU Streamwood did not provide these values as output. A range of depletion rates from less than 1% to more than 5% was reported in (Welty et al., 2002) where it was stated that depletion rates reported by "most authors" were in the 1% to 2% range. The depletion rates used here were constant depletion rates computed from the OSU Streamwood LWD values assuming a 1.5% depletion rate and averaging over the 160 year time horizon. Fourth, negative depleted AFLWD values were set to zero, and then cumulatively summed to produce the integrated amount of estimated in stream LWD compatible with OSU Streamwood.

3 Results and discussion

3.1 Regional AFLWD results

The AFLWD simulation results derived from the Douglas-fir reference data set for western Washington are presented as scatter plots of volume *vs.* pieces in Figure 5 and Figure 6 for stream/log size classes A and E, respectively. The scatter plots provide an indication of the shapes of the joint distributions for AFLWD volume and pieces for each stream/log size class. The distribution of AFLWD volume and pieces for the large stream and large functional log size, class A, is tall and narrow, and essentially linear, with the number of pieces ranging from 0 to 20 pieces per 328.1 feet of stream reach and volumes ranging from 0 ft^3 to over 8000 ft^3 per 328.1 feet of stream reach. The distribution of total AFLWD volume and pieces for the small stream and small functional log size, class E, is tall and wide, and is strongly heteroschedastic, with the number of pieces ranging from 0 to nearly 140 pieces per 328.1 feet of stream reach and volumes ranging from 0 ft^3 to over 9000 ft^3 per 328.1 feet of stream reach. These figures indicate that the majority of the AFLWD volume comes from large logs that must be located closer to a stream, and that for a given number of AFLWD pieces the range of AFLWD volume values is large.

The AFLWD volume and piece count values are strongly right skewed, which contributes to their heteroschedasticity, making the use of simple marginal distribution based lower bounds for assessment more difficult to do properly. As an example of this, Figure 7 shows the joint distribution of the AFLWD volume and pieces with approximate probability contours, an estimate of the mode, and median based lower bounds, not recommended, but frequently used. The acceptance region for assessments is the upper right above and to the right of the two median lower bounds, and only 31% of the points would be accepted using this type of assessment. While straightforward to compute and easy to use, the simple median lower bounds exclude the mode, or most likely value of the AFLWD volume and piece count joint distribution, as well as excluding the majority of the most likely points around the mode. Given that the mode is the most likely point, an assessment procedure should be aiming for it, not excluding it. An example of such an assessment procedure is given below when discussing the management scenario results.

Estimates of mean source distance for AFLWD volume and pieces are presented in Table 2, and are consistent with values reported in the literature (McDade et al., 1990,

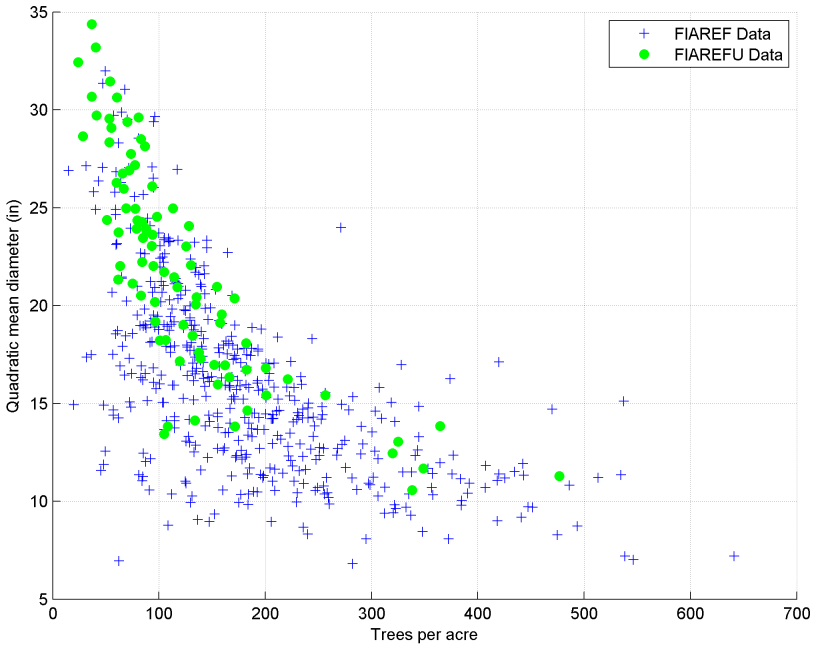

Figure 4: Quadratic mean diameter *vs.* trees per acre for the FIAREF and DFCVDS reference data sets and an unmanaged subset of the FIAREF reference data set.

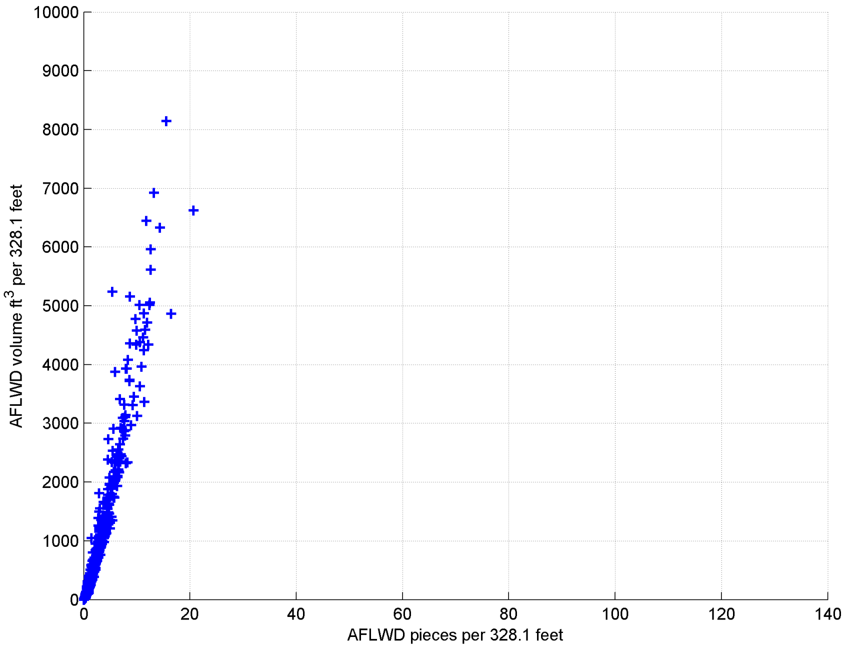

Figure 5: Scatter plot of AFLWD volume *vs.* pieces for stream/log size class A.

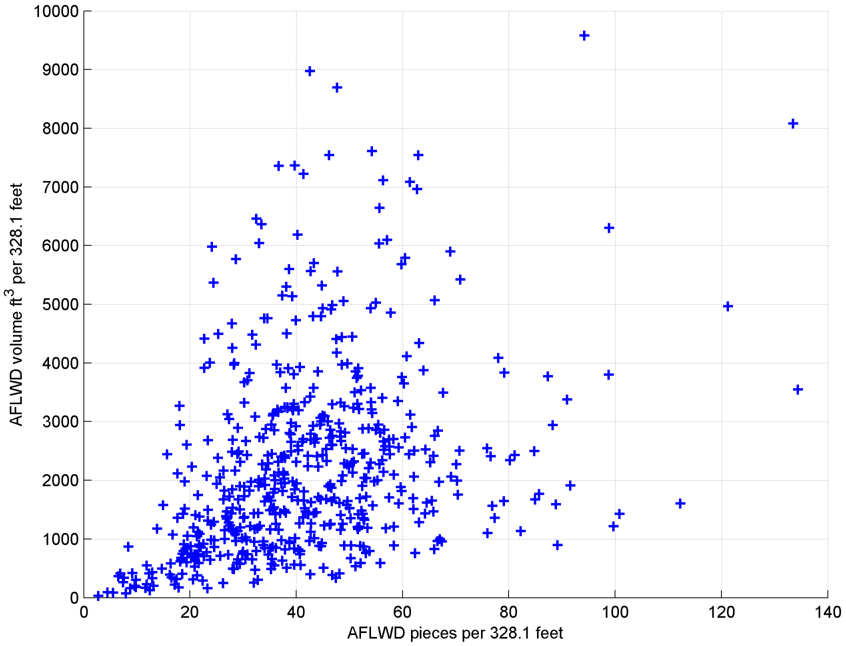

Figure 6: Scatter plot of AFLWD volume *vs.* pieces for stream/log size class E.

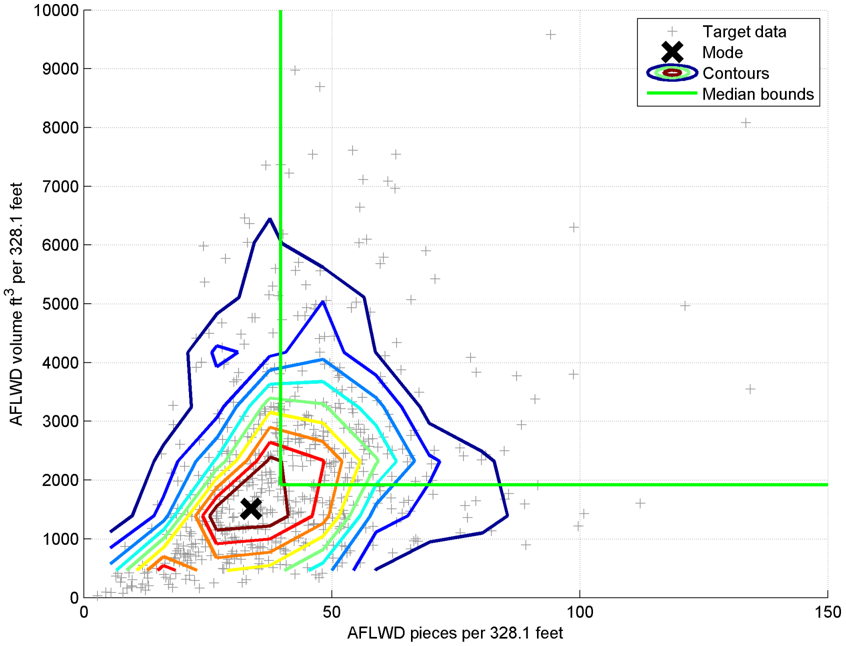

Figure 7: Joint distribution of the AFLWD piece count and volume metrics with an estimate of the mode, approximate probability contours, and median based lower bounds. Note that the median based lower bounds miss the mode, the most likely point of the distribution. The region surrounding the mode should be the region targeted by assessment criteria.

Table 2: AFLWD mean source distance results for accumulation percentages of 99%, 95%, 90%, 80%, and 50% for stream/log size classes A and E.

Percent	Size Class A		Size Class E	
Accumulation	Pieces	Volume	pieces	volume
99%	89 ft	76 ft	130 ft	102 ft
95%	57 ft	46 ft	98 ft	72 ft
90%	41 ft	32 ft	79 ft	57 ft
80%	23 ft	19 ft	57 ft	41 ft
50%	4 ft	4 ft	24 ft	17 ft

Van Sickle and Gregory, 1990, Welty et al., 2002). Three features are apparent from an examination of the table. First, mean source distances for stream/log size class A are much smaller than the comparable source distance for stream/log size class E. This is due to the fact that large logs are produced by large trees closer to a stream. Second, for a given accumulation percentage the source distance for volume is less than that for pieces. This is, again, related to the fact that trees of a given size further from a stream produce smaller logs, which have smaller volumes, and hence produce the shorter source distances due to an inherent volume based weighting of the distances relative to the number of pieces. Third, increases in source distance for marginal increases in accumulation percent are relatively large, for example, moving from 90% to 95%, produces increases in source distance of between 15 feet and 20 feet for both stream/log size classes, or approximately 10% of the total width of the RMZ. This feature of the source distances is a side-effect of fact that the independent tree fall assumption does not take into account the lower probability of stream intersection due to the intervening trees.

3.2 Management scenario results

Results for the management scenario assessment relative to the AFLWD volume and piece target derived from the reference data set are given in Table 3. At first glance, the results are surprising: the two management scenarios with the greatest total harvest amounts over time performed relatively well with 66% and 79% acceptance for the 50 ft No Harvest and Bio-pathway scenarios, while the No Action scenario and the two Forest and Fish scenarios that have wide no harvest zones adjacent to the stream achieved only 3% acceptance. From Figure 8 a plot of the AFLWD metrics computed using the sample plots from the reference data set with the assessment results for the management scenario trajectories, it is clear that the AFLWD trajectories for the No Action and the Forests and Fish scenarios fall within the range of the targeted AFLWD values, but well outside the region containing the majority of the data points. The primary reasons for the overestimation of these AFLWD trajectories relates to the TPA retained by the growth model relative to the distribution of TPA values in the reference data.

The reference data set represents the distribution of actual Douglas-fir dominated and mixed forest stands, but the growth model grows an idealized stand. The presence of small canopy gaps caused by windthrow, clumping, fires, etc. in the actual stands reduces

Table 3: Management scenario AFLWD assessment results for a 90% acceptance region and total functional LWD.

Management Scenario	Percent accepted
50 ft No Harvest	66%
Bio-pathway	79%
FF Option 2 $\geq$ 10 ft	3%
FF Option 2 $<$ 10 ft	3%
No Action	3%

the numbers of trees that are available to produce AFLWD relative to the idealized stand, and contributing to the over prediction of AFLWD by the management scenarios with wide no harvest zones relative to the actual stands. The simulated stands also used as an initial condition a stand that was planted at a much higher density than would have occurred in a naturally regenerated stand, again providing a boost to the AFLWD trajectory values for the management scenarios with wide no harvest zones due to the greater number of trees present in the simulated stands based on the initial condition. The 50 ft No Harvest and Bio-pathway management scenarios had lower overall TPA values, making them more similar to the stands in the reference data set, and, therefore, improving their acceptance percentages.

The total number of AFLWD pieces produced over time is directly related to the width of the no harvest zone adjacent to a stream and the cumulative amount of harvest over time, see Figure 9. The Bio-pathway scenario has the narrowest no harvest zone and produces the smallest total number of AFLWD pieces over time, beginning to differentiate from the other scenarios after the second thinning event at age 35. After age 70, the time of the final thinning event and the underplanting, the total number of AFLWD pieces appears to remain constant, or to, possibly, be slowly increasing. Only the first harvest at 50 years is visible in this trajectory. The 50 ft No Harvest scenario produces a total number of AFLWD pieces between the Bio-pathway and the remaining management scenarios, beginning to differentiate from the Forests and Fish and No Action scenarios after the first thinning event at age 35. The three harvest events are clearly visible, and there is a decline in total AFLWD pieces after each harvest. Prior to the second and third harvest events, there is a slight recovery of AFLWD pieces, as trees outside the 50 foot no harvest zone become large enough to intersect with the stream. The two Forests and Fish scenarios and the No Action scenario increase together until the first harvest, when the number of AFLWD pieces for the FF Option 2 $<$ 10 ft scenario begins to decline. The FF Option 2 $\geq$ 10 ft scenario begins its decline next at age 85, the second thinning of the second rotation in the inner and outer management zones. The total number of AFLWD pieces for the two Forests and Fish scenarios continue to decline, with the second and third harvest events being visible as slightly steeper declines at 100 and 150 years.

The relationships among the management scenarios for total AFLWD volume were similar to those for pieces, with differentiation among the scenarios beginning after the first harvest at age 50, and the trajectories are shown in Figure 10. The Bio-pathway scenario produced the smallest values for total AFLWD volume, with the 50 ft No Harvest scenario producing the next largest, and also differentiating itself after the first harvest, followed by,

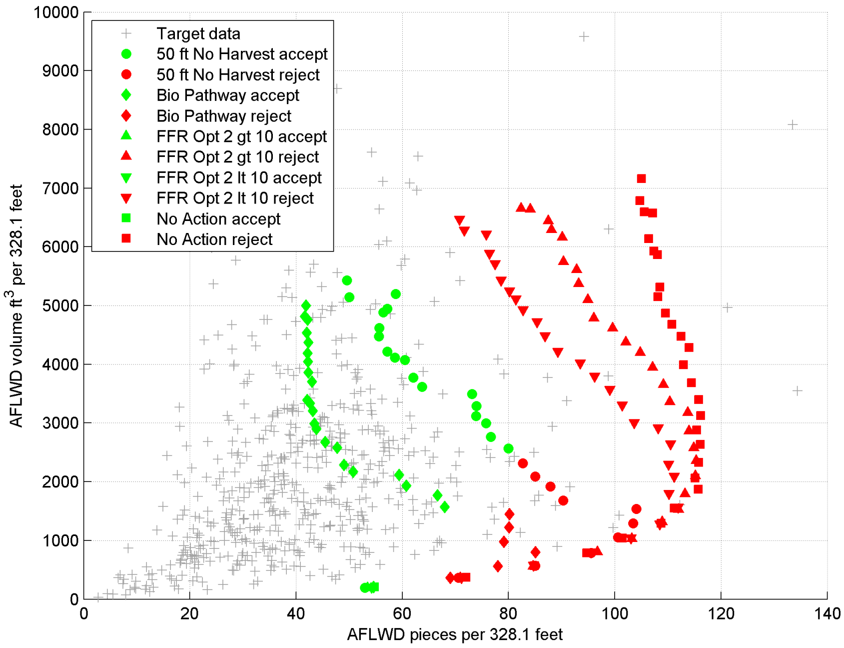

Figure 8: Management scenario assessment results.

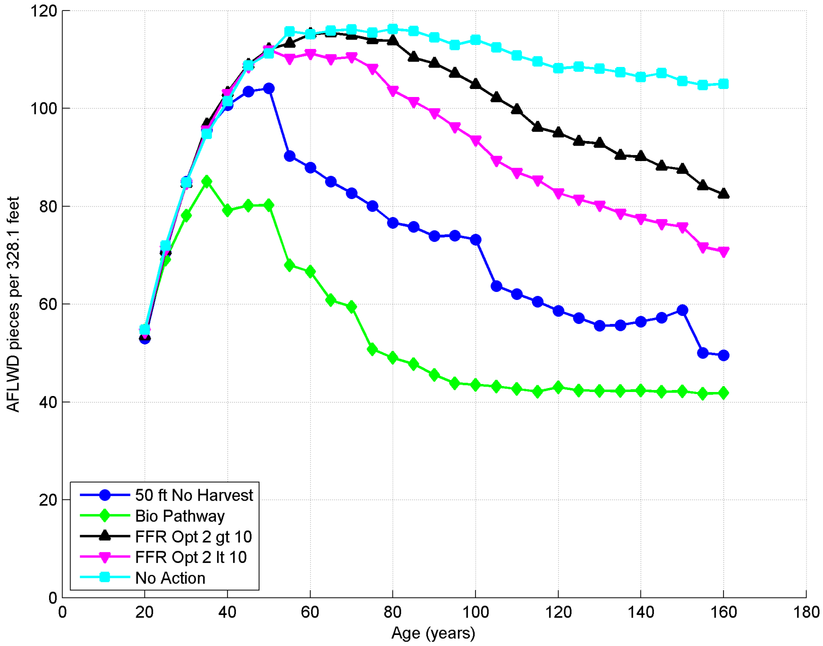

Figure 9: Management scenario AFLWD pieces *vs.* age for stream/log size class E.

in order of increasing total AFLWD volume, the FF Option 2 $<$ 10 ft, FF Option 2 $\geq$ 10 ft, and No Action scenarios. The two Forests and Fish scenarios and the No Action scenario remained nearly equivalent until the second harvest event, where their differentiation began, and became somewhat greater after the second harvest. The delay in the differentiation among the Forest and Fish scenarios and the No Action scenario is a direct result of the fact that differentiation cannot occur until trees beyond 80 feet from the stream for the FF Option 2 $<$ 10 ft scenario and 100 feet from the stream for the FF Option 2 $\geq$ 10 ft scenario become large enough to fall and enter the stream, and that 99% of the volume accumulation occurs within 100 feet of the stream. It is, therefore, extremely unlikely that significant volume contributions will occur beyond the 100 foot point.

The number of large AFLWD pieces for stream/log size class A tells a different story, and the trajectories are shown in Figure 11. If large AFLWD logs are desired, the Bio-pathway scenario produces the most large logs over the 160 year time horizon, differentiating itself from the other four scenarios at age 90. The thinning and harvest events are also visible in the Bio-pathway trajectory as changes in the slopes of the lines during the five year intervals between points. The other four management scenarios are essentially indistinguishable from one another over the entire time horizon with regard to the production of large AFLWD logs. This was to be expected given that these management scenarios all had no harvest zones that were at least 50 feet wide and 95% of the large class A AFLWD pieces occurred within 57 feet of the stream.

Relationships among the management scenarios for AFLWD volume and stream/log size class A, the large AFLWD logs, were identical to those for pieces, and are shown in Figure 12. The shorter source distance to the stream the volume of large LWD logs has smoothed out the volume trajectory somewhat relative to the trajectory for number of large pieces, but the thinning and harvest events are still visible.

A key aspect of the ecology of in stream LWD is the idea of *functional* LWD, e.g., LWD that forms pools or waterfalls, enhances bank stability, or provides habitat. Larger streams require larger LWD logs to function. This can be thought of as a need for the “stickiness” of LWD logs, and larger streams require larger logs so that they can “stick.” The Bio-pathway management scenario was designed to create a multi storied canopy with larger trees between 25 feet and 80 feet from a stream with a 25 ft no harvest zone directly adjacent to a stream. All of the other management scenarios had at least a 50 foot wide no harvest zone directly adjacent to a stream. The narrow, 25 foot, no harvest zone coupled with the multiple thinning and underplanting has allowed large trees to develop close enough to the stream to provide large AFLWD pieces.The Bio-pathway scenario, therefore, worked, and it or a similar strategy could prove useful when choosing management options intended to supply LWD to large streams.

3.3 AFLWD comparison to OSU Streamwood

Results of the comparison of the AFLWD metrics to output from the OSU Streamwood LWD model are presented in Figure 13 and Figure 14 for number of pieces and volume, respectively, per 328.1 feet of stream reach. In each figure the OSU Streamwood trajectory consists of mean values plus or minus one standard deviation error bounds based on 250 simulation trials computed the model using its internal forest growth model for an unmanaged forest,

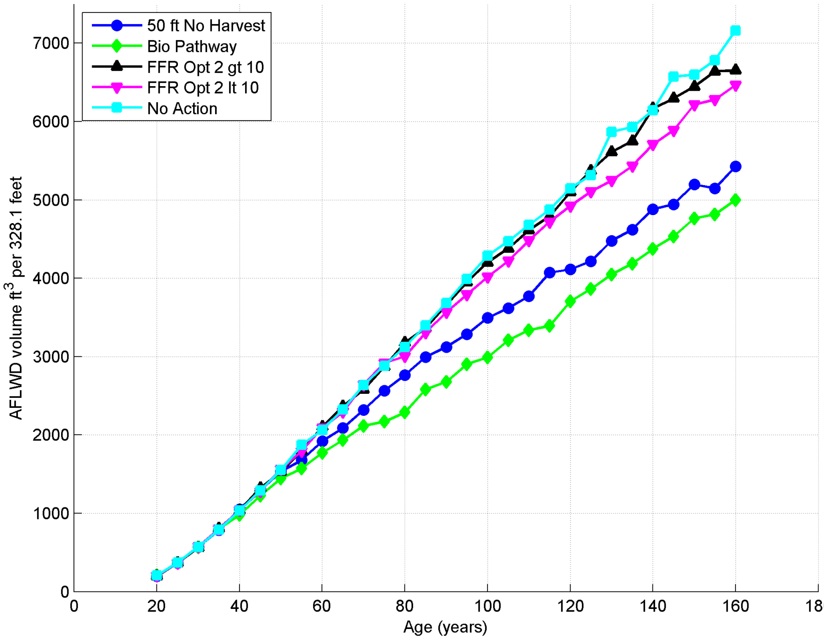

Figure 10: Management scenario AFLWD volume *vs.* age for stream/log size class E.

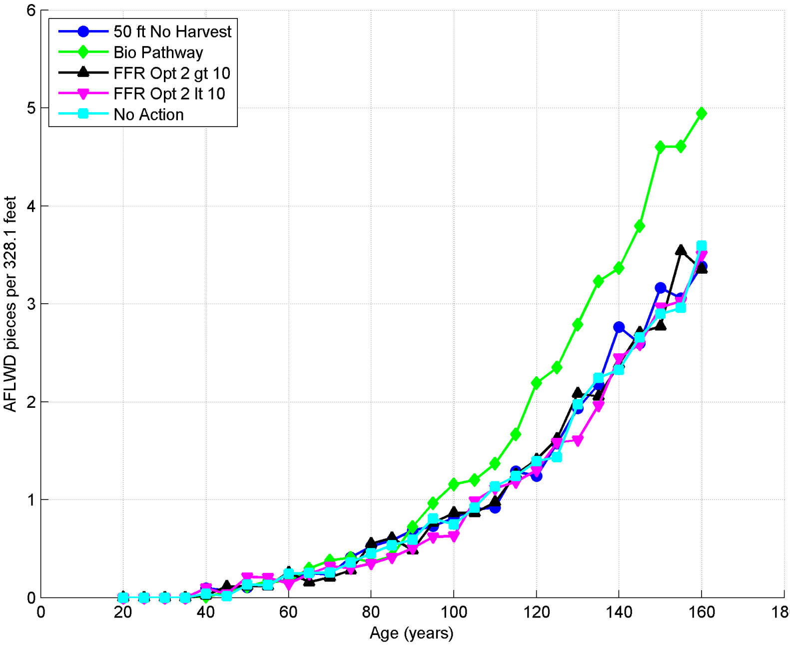

Figure 11: Management scenario AFLWD pieces *vs.* age for stream/log size class A.

and the AFLWD trajectory is the mean of 100 bootstrap simulation trials. The results speak for themselves, indicating that the model used to produce the AFLWD volume and piece count metrics is consistent with an ecologically oriented dynamic model for in stream LWD once depletion is taken into account. The results also indicate that the AFLWD volume and piece count metrics are statistically equivalent to their respective outputs from OSU Streamwood, since the AFLWD trajectories are within the error bounds produced by the OSU Streamwood model.

The differences in the shapes of the AFLWD and OSU Streamwood trajectories are driven by differences in their respective mortality profiles, particularly early mortality, as shown in Figure 15. The OSU Streamwood model has much higher early mortality, between 30 and 70 years, and lower later mortality, after 70 years, than the SMC-ORGANON model used for the AFLWD No Action scenario. Since OSU Streamwood uses only mortality trees to produce in stream LWD, the early mortality quickly drives up the LWD piece count and volume values, while the slower early mortality of SMC-ORGANON causes the AFLWD piece count and volume values to lag initially. For volume there is a crossover point at 70 years where the AFLWD values become greater than the OSU Streamwood values, and this is a direct consequence of the SMC-ORGANON mortality becoming greater than the OSU Streamwood mortality at that age and the fact that larger trees are dying. After 70 years, the OSU Streamwood mortality steadily declines, while the SMC-ORGANON mortality is more sporadic, but usually greater than the OSU Streamwood mortality, and this is what drives the increasing differences in the mean AFLWD and OSU Streamwood volume trajectories, more larger trees dying in the SMC-ORGANON growth model. Similar relationships exist for the number of pieces, and are not discussed.

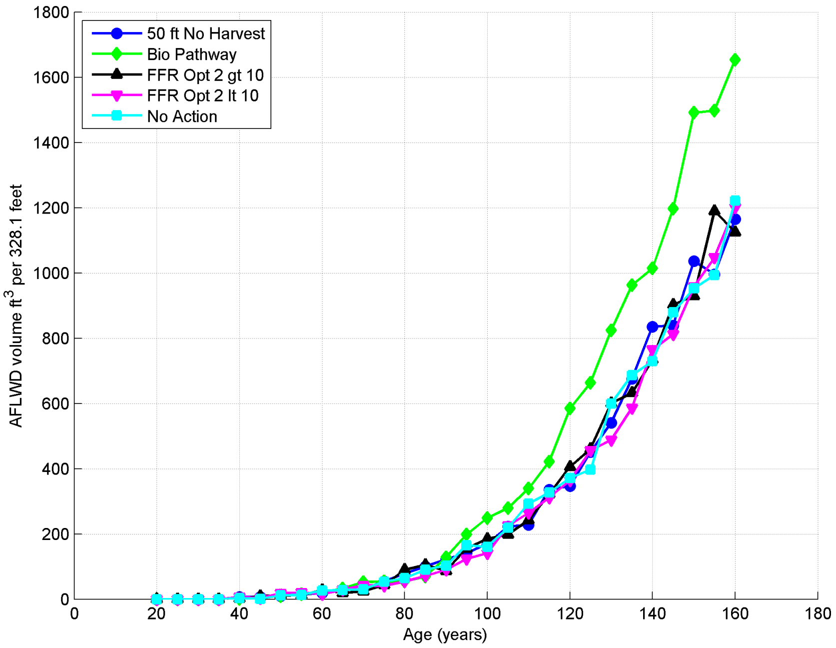

Figure 12: Management scenario AFLWD volume *vs.* age for stream/log size class A.

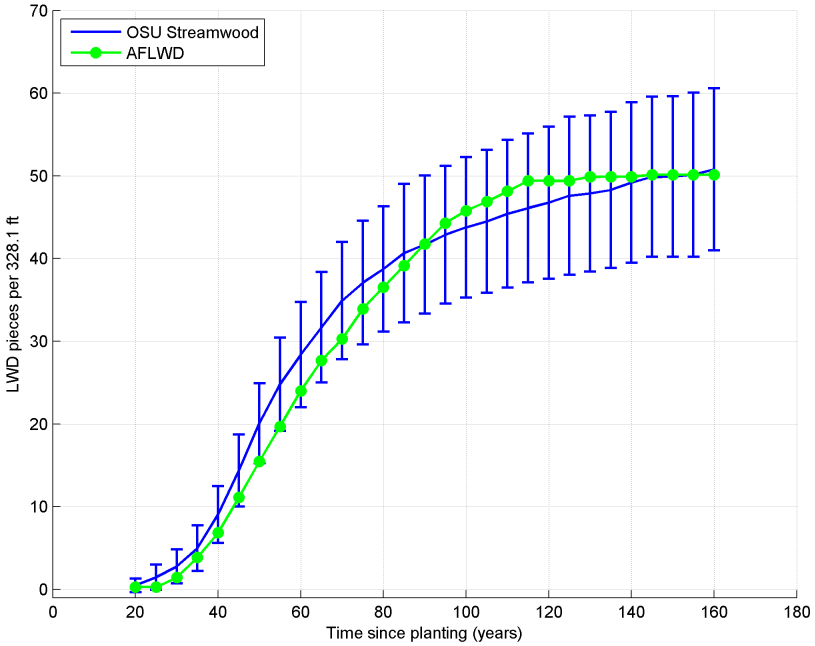

Figure 13: AFLWD piece count comparison to OSU Streamwood with one standard deviation bounds computed by OSU Streamwood.

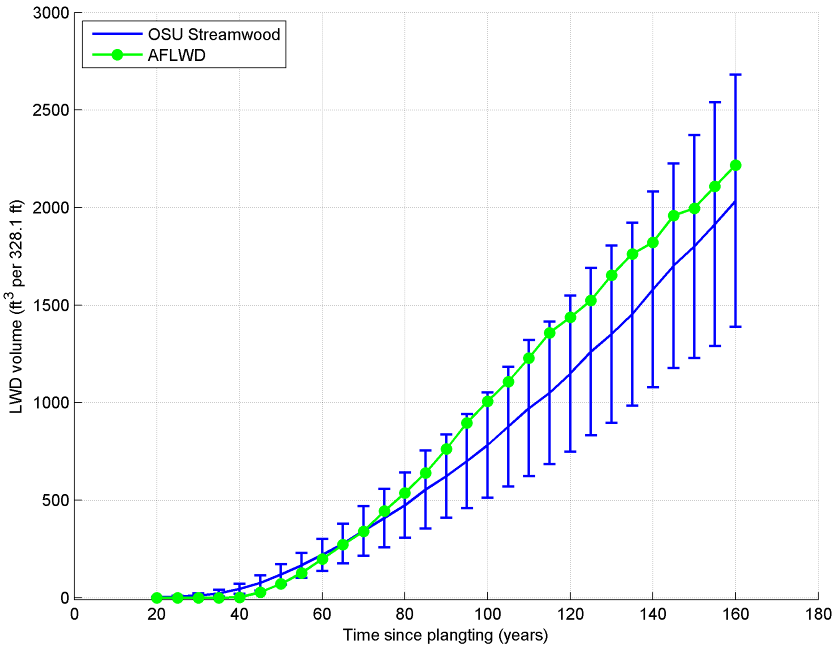

Figure 14: AFLWD volume comparison to OSU Streamwood with one standard deviation bounds computed by OSU Streamwood.

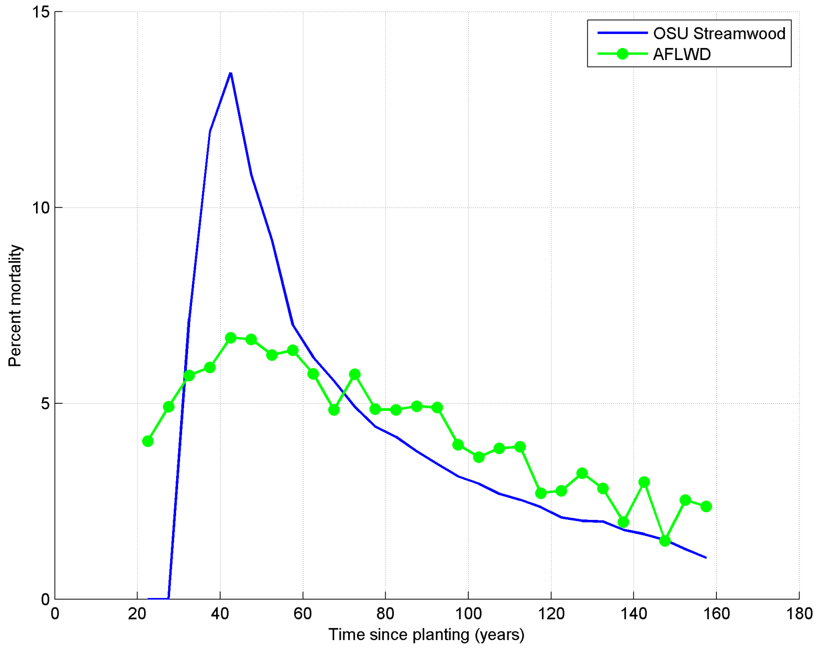

Figure 15: AFLWD mortality comparison to OSU Streamwood.

4 Conclusions

The results presented here are consistent in general magnitude and distribution with results reported from empirical studies and from other LWD models, and in particular, those studies and models from the Pacific Northwest. The reference data set and the AFLWD metrics produced from it, are, therefore, consistent with the known ecology of LWD production, to the extent that it is represented in the AFLWD metrics model and others, e.g., OSU Streamwood, and the AFLWD approach has also been demonstrated to be consistent with the currently-accepted scientific approaches to modeling in stream LWD via the direct comparison with OSU Streamwood, a currently-accepted and used model of in stream LWD dynamics in the Pacific Northwest.

The current and future states of a riparian forest are of primary interest from a management and regulatory perspective, and effective models and metrics within this context should acknowledge this temporal constraint and incorporate it. The AFLWD model and metrics do this. Further, the AFLWD metrics are easier to compute than in stream measures of LWD, and they are also equivalent to a class of ecologically oriented individual tree models of in stream LWD. The AFLWD model and metrics provide a relevant simplification to the problem of regulating and managing riparian forests to produce LWD while maintaining the underlying ecological integrity. The AFLWD model should, therefore, prove to be an effective tool within a management and regulatory context.

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