An Individual Tree Simulation Model for Multi-zone Managed Riparian Buffers (DRAFT)

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Abstract

An individual tree based simulation framework for estimating the characteristics of managed riparian forest buffers having multiple treatment zones was developed. Within the simulation framework, tree lists were used to provide descriptions of riparian forest stands. Each tree list was assumed to be one instance of a stand having the described characteristics, randomly drawn from a larger pool of similar stands. A resampling strategy within the simulation framework was used to generate multiple simulated stand descriptions, tree lists, that were then used to investigate the distributions, mean values, and variability of a number of riparian buffer characteristics for a variety of riparian buffer management scenarios.

A forested riparian buffer was assumed to be modeled by a one acre region directly adjacent to one side of a stream, having a maximum width B_w, measured perpendicular or up slope to the stream, and a stream reach, measured along the stream, of $43560/B_w$ ft. Riparian buffer management scenarios were defined by specifying a partition of a one acre riparian buffer into at most five separate management zones $I_k = [B_{k-1}, B_k]$, $k = 1, 2, \ldots, K$, with $1 \leq K \leq 5$, $B_0 = 0$, $B_K = B_w$, and an assignment of one of 16 defined management options, or prescriptions, to each management zone. Management options representing different thinning and harvest strategies were defined using tree lists containing the standing, live trees obtained at five year intervals from 140 year projections of a one acre stand derived from an initial inventory based on a 20 year old, managed stand of Douglas-fir (*Pseudotsuga menziesii*).

Over 100 riparian buffer management scenarios having one to three management zones were designed and simulated for a one acre buffer having a width $B_w = 170$ ft. The objective was to identify management scenarios that were capable of providing a substantial degree of benefit or protection to their adjacent streams, measured by their potential to produce functional large woody debris (LWD) for six stream size classes ranging from 3.3 ft to 75.5 ft, as well as providing economic benefit to the landowner. The simulation results indicated that managed riparian buffers could potentially produce significant amounts of functional LWD for all stream size classes, with the amount varying based on the intensity of management.

Management scenarios with large no management areas directly adjacent to a stream produced less potential LWD for the larger stream size classes than management scenarios that permitted thinning treatments closer to a stream. Management scenarios that included an underplanting to promote the development of an understory produced a greater number of potentially functional LWD pieces, but a smaller amount of potentially functional LWD volume, than equivalent scenarios without the underplanting. These results demonstrate the complex nature of riparian forest management, and indicate the existence of potential trade-offs among several desirable characteristics of riparian forests, and identify a need for a better understanding of the roles of LWD in streams of different sizes. Overall, these results show that riparian management scenarios that simultaneously provide benefit to a stream and economic benefit to a landowner are clearly possible, and that they may not require wide no management buffers.

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Acknowledgements

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Chapter 1

Introduction

The potential impacts of management on the structure and function of riparian forests has become an important forest management issue in the Pacific Northwest and in Washington State (FFR, 1999, WFPB, 2001, Ehlert and Mader, 2000, Fairweather, 2001). These functions include, but are not limited to, bank stability, shade production, habitat for wildlife, and the production of large woody debris (LWD). An understanding of the functions provided by managed forests that are adjacent to streams and their relationships to the inherent variability of natural forests is crucial for the development of effective forest management practices and policies. The ability of a forest adjacent to a stream to produce LWD that may be recruited into a stream channel over time has become of particular importance (FFR, 1999), since 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, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Welty et al., 2002).

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 an adjacent forest, or some of the characteristics of the LWD, (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Cross, 2002, Welty et al., 2002, Gehringer, 2003). Two of these models, the riparian aquatic interaction simulator or RAIS (Welty et al., 2002) and the riparian-in-a-box or RIAB model (Beechie et al., 2000), have been linked to forest growth or stand development models. The SMC variant of ORGANON (Hann et al., 1997), version 6.0, and the Forest Vegetation Simulator (FVS) (Donnelly, 1997), respectively, were used to enable the projection of LWD contributions to streams over time. RAIS and RIAB could be used with other forest growth or stand development models, provided their requisite input data could be obtained from the chosen model.

Both RAIS and RIAB based LWD recruitment on stand mortality and used the LWD recruitment model of Van Sickle and Gregory (1990) coupled with an LWD depletion rate to estimate the accumulation of LWD in a stream from its adjacent forest over time. RAIS and RIAB also based their estimates of LWD accumulation on the average dimensions, quadratic mean diameter and average height by species, of the trees that died in a particular time interval, and both models assumed that mortality was uniformly distributed throughout the riparian stand. RAIS and RIAB both allowed riparian stands to be thinned, with the thinning being uniform throughout the stand. RAIS did not consider ingrowth, but RIAB allowed for the planting of trees after thinnings, via FVS, during its projections. Both RAIS and RIAB included mechanisms permitting the computation of potentially functional LWD, based on minimum LWD log diameters for differing stream sizes indicate by bank-full widths. RAIS accomplished this through a user specified minimum diameter (Welty et al., 2002), and RIAB used a regression equation for minimum pool forming LWD log diameters based on stream bank-full width (Beechie and Sibley, 1997, Beechie et al., 2000).

The emphasis of RAIS and RIAB on stand mortality to estimate the potential recruitment of LWD into a stream, coupled with the use of an average tree to represent the trees of each species that died in a particular time interval, and the limited management options may reduce the effectiveness of these models in practice for several reasons. First, the rates of LWD recruitment into streams are highly variable and are not known with certainty (Welty et al., 2002). Second, LWD recruitment into streams has an episodic nature, with large LWD additions caused by windthrow, bank erosion, or flooding (Van Sickle and Gregory, 1990), that occur sporadically in time, rather than continuously, so mortality may not provide an adequate indication of recruitment. Third, the recruitment of LWD into a stream is highly dependent on the physical locations and sizes of individual trees (McDade et al., 1990, Van Sickle and Gregory, 1990, Robison and Beschta, 1990, Cross, 2002, Gehringer, 2003) relative to a stream, and the use of an average tree to represent mortality, assumed to be uniformly distributed throughout a stand, may not provide sufficient detail, relative to the manner in which trees fal and enter a stream to produce LWD. Fourth, the uniform application of a thinning treatment throughout a riparian stand severely restricts the types of riparian forest structures, as well as the potential benefit to a stream, that may be obtained by using a more flexible approach that permitted the application of different management options to separate management zones defined within a riparian stand. Finally, given the high variability of the input, output, and instream processes affecting amounts and locations of instream LWD within a watershed, the modeling of these processes, while ecologically important, may not be the most effective strategy from a management or regulatory perspective, since their inclusion may introduce significant modeling uncertainties.

An individual tree based simulation framework for modeling the development of managed riparian buffers is proposed. The simulation framework uses an LWD availability model (Robison and Beschta, 1990, Cross, 2002, Gehringer, 2003) rather than an LWD recruitment model (McDade et al., 1990, Van Sickle and Gregory, 1990) to provide estimates of potentially available instream LWD. The LWD availability models provide instantaneous estimates of the amounts of LWD that *could* potentially enter a stream in the future, rather than attempting to estimate the amounts of LWD that *would* be recruited into a stream. The proposed simulation framework directly recognizes the discrete nature of trees by considering the potential, individual contribution of each tree present in a managed riparian buffer and, in particular, may be used to estimate the potential for the production of instream LWD. This is of particular importance since tree size and location relative to a stream have a significant impact on the production of LWD (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Cross, 2002, Welty et al., 2002, Gehringer, 2003), and average tree based or spatial aggregation methods for estimating LWD production may not provide a sufficient level of detail. Finally, the proposed simulation framework allows the definition of multiple management zones, parallel to a stream, within a managed riparian buffer, and the application of separate management options within each zone. By using multiple management zones with different management options it should be possible to design variable density riparian management strategies that simultaneously provide significant benefit to a stream and economic benefit to a forest land owner.

Within the simulation framework, it was assumed that a stand description, whether represented by an average tree size and stand density, a tree list without tree locations, or a tree list with tree locations, produced by any of the model types, at a particular point in time, represented a single instance of a stand having the described characteristics. The particular stand obtained was, therefore, assumed to be randomly drawn from a larger set of possible stands that were representative of the described characteristics, an assumption comparable to that made when sampling actual forests to obtain representative forest inventories (Husch et al., 1993, Vanclay, 1994). A resampling strategy (Efron, 1982, Efron and Tibshirani, 1998, Davison and Hinkley, 2003) was used to generate multiple simulated stand descriptions, using individual trees, based on the description for a particular stand at a particular time. By considering the resampled stands to be separate, representative sample stands, estimates of mean values and their variability, as well as the distibutions, for stand characteristics of interest may be obtained.

Like RAIS and RIAB the simulation framework defined here relies on forest growth or stand development models to project current stand conditions into the future. While the specific form of reliance on the forest growth or stand development models differs somewhat among RAIS, RIAB, and the simulation framework used here, a brief discussion of the general forest growth and stand development model types seems warranted to provide some additional context for the use of models like RAIS, RIAB, and the simulation framework described here.

Forest growth and stand development models may be classified into three general types: whole stand models, distance-independent individual tree models, and distance-dependent individual tree models (Vanclay, 1994). Each general type of model may further be subdivided into deterministic or stochastic varieties. The deterministic models always produce identical results for identical initial stand conditions, and the stochastic models produce a range of similar results for identical initial stand conditions based on one or more randomization procedures built into the model. Gap models (Botkin et al., 1972, Shugart, 1984, Botkin, 1993) were considered to be distance dependent individual tree models.

A nested hierarchy of detail exists among the three types of forest growth or stand development models. Whole stand forest growth models provide the least detail, typically representing stand development by considering the size of a typical or average tree and stand density and their changes over time. The DFSIM model for coastal Douglas-fir (*Pseudotsuga menziesii*) (Curtis et al., 1981), the dynamic model for plantation Douglas-fir by Gehringer (2001) , and the PIPESTEM model (Valentine et al., 1997) are examples of this type of model, and there are many others in the literature.

The distance-independent individual tree forest growth models provide an intermediate level of detail, typically representing stands using tree lists containing at least the diameter, height, species, and trees represented per acre for a set of trees. These models generally represent stand development at two scales by projecting the growth of individual trees subject to constraints imposed by size-density relationships and mortality. Stand development and tree growth are projected based on the average characteristics of the stands and trees, and no direct use of specific localized inter-tree competition or tree location informations are used. These models do not include edge effects, nor do they allow stand density to vary within a single stand except by dividing the stand into smaller management units to model each unit separately, since tree locations are not used. The ORGANON model, and its variants, for Oregon and Washington (Hann et al., 1997), the FVS model (Donnelly, 1997) and its variants, and the STEMS model (Belcher et al., 1982), are all examples of this type of model. This type of forest growth model has become the most popular and there are many examples that may be found in the literature for a variety of regions.

The distance-dependent individual tree forest growth models provide the highest level of detail, typically representing stands as tree lists that include the actual locations of each tree within the stand, in addition to the tree size and species information. These growth models, necessarily, represent each tree within a stand separately. The distance-dependent growth models generally represent stand development at three scales, projecting the growth of individual trees including branches, subject to constraints imposed by the neighboring trees within their local environment, and by stand level constraints imposed by size-density relationships and mortality. These models project stand development and tree growth based on specific, local inter-tree competition, making direct use of the spatial relationships among the trees. They may include edge effects, and by using the locations of each tree, they allow stand density to vary spatially within a stand. The Tree and Stand Simulator (TASS) (Mitchell, 1975) is an example of a distance-dependent forest growth model. Several other examples may be found in the literature.

Forest growth models that produce tree lists containing multiple trees, with each tree representing one or more trees per acre are preferred for use within the simulation framework used here. Tree list based descriptions contain more information about the individual trees than may be obtained by using a stand level forest growth model or summarized output from an individual tree based growth model, typically a simple stand summary containing the average tree size and stand density.

In the next section, Chapter 2, the general simulation framework specifying a simulation model for multiple zone managed riparian buffers is described. This is followed by an application of the simulation framework to obtain estimates of mean expected levels of potentially available LWD volume and pieces, and their variability, for managed Douglas-fir riparian buffers in western Washington. The application is described in Chapter 3, followed by results of the simulations in Chapter 4. A brief discussion of the performance of the simulation model and its limitations are provided in Chapter 5, with some concluding remarks in Chapter 6.

Chapter 2

Methods

The simulation model developed to investigate the potential consequences and variability of different riparian buffer management scenarios is described in this chapter. The model was designed to allow the application of different management options within each of K management zones in a riparian buffer. Management zones were assumed to be adjacent strips running parallel to a stream, starting at the stream bank and proceeding away from the stream, for a fixed size riparian area adjacent to the stream. The management zones within a riparian buffer were defined using a partition, allowing the zones within a buffer to have varying widths. The simulation model may be used to simulate and compare riparian buffer management scenarios at either a fixed point in time or over a sequence of times, requiring only tree lists for the management options that were applied in the riparian buffer management zones for the time, or times, of interest.

The riparian buffer or riparian management area is first defined in Section 2.1. This is followed by the definitions for a management option, in Section 2.2, and for a management scenario, in Section 2.3. Next, the procedures used to generate representative tree lists from a management option are defined in Section 2.4. Finally, the simulation framework that was used to perform the management scenario simulations is specified in Section 2.5.

2.1 Riparian buffer area

A managed riparian buffer in the simulation model was defined to be a one acre region directly adjacent to a stream on only one side, having a width B_w, measured perpendicular or upslope to the stream, and having a corresponding stream reach $B_r = 43560/B_w$ ft. For simplicity the stream bank was assumed to be a straight line. The buffer was partitioned into K nested management zones, $1 \leq K \leq K^{\max}$, relative to a stream, defined by a set of adjacent buffer intervals $I_k = [B_{k-1}, B_k]$, $k = 1, \ldots, K$, where $B_{k-1} < B_k$, $B_0 = 0$, $B_K = B_w$, and $K^{\max}$ is the maximum number of management zones. The partition defines a set of adjacent strips parallel to the stream, each having a length of B_r, within the buffer. Each management zone, then, represents a fraction of a riparian acre

$$f_k = \frac{(B_k - B_{k-1}) \cdot B_r}{43560}, \tag{2.1}$$

where $\sum_{k=1}^{K} f_k = 1$. For computational purposes the interior zone boundaries B_k, $k = 1, 2, \ldots, K-1$ were assumed to be contained in the buffer zone that was closer to the stream. A maximum of five management zones, $K^{\max} = 5$, are currently allowed by the simulation model within a managed riparian buffer.

2.2 Riparian management options

A *riparian management option* was defined by a sequence of canonical tree lists T_l representing the standing, live trees on a forested riparian acre corresponding to a sequence of simulation years y_l, for $l = 0, 1, 2, \ldots, Y$, where y_0 is the initial simulation year and y_Y is the final simulation year, $y_{l-1} < y_l$ for $l = 1, 2, \ldots, Y$. The total simulation length was then $y_Y - y_0$ years. The trees in each canonical tree list T_l were assumed to be representative of the stand conditions for the point in stand development identified by the simulation year y_l and the management option that they represented.

Each tree list contained N_{T_l} standing, live trees T_{li}, represented as six dimensional vectors $T_{li} = [N_{li}, D_{li}^{\text{dbh}}, H_{li}, S_{li}, I_{li}^{\text{leave}}]^T$, containing the elements N_{li}, the number of standing, live trees per acre (TPA) represented by tree i in simulation year y_l; D_{li}^{dbh}, the diameter at breast height (DBH) of tree i in simulation year y_l; H_{li}, the height of tree i in simulation year y_l; S_{li}, the species of tree i in simulation year y_l; and I_{li}^{leave}, a leave tree indicator for tree i in simulation year y_l, as defined by Equation 2.2.

$$I_{li}^{\text{leave}} = \begin{cases} 1 & \text{if tree } i \text{ in tree list } T_l \text{ was a leave tree} \\ 0 & \text{otherwise} \end{cases} \tag{2.2}$$

A leave tree was a tree that is intentionally left after a harvest to be carried forward, either indefinitely or for at least one harvest cycle, in the management option. The stand density, measured as TPA, represented by the tree list T_l for simulation year y_l was $N_l = \sum_{i=1}^{N_{T_l}} N_{li}$. If $N_{li} = 1$ for all trees in the tree list, $i = 1, 2, \ldots, N_{T_l}$, then $N_l = N_{T_l}$, that is, the number of trees in the tree list equals the number of TPA represented by the tree list.

While the tree lists T_l were assumed to represent only the standing, live trees in the one acre managed riparian buffer, this assumption was not necessary. It was made for simplicity based on the fact that snags or down woody debris on the ground in a forest originate from the pool of standing live trees. If the presence of standing dead trees or snags within a riparian buffer were also desired, this could easily be accomplished by adding a new element to the vectors representing the individual trees in the canonical tree lists. This new element would be an indicator identifying whether the tree was alive or dead, as in Equation 2.3.

$$I_{li}^{\text{dead}} = \begin{cases} 1 & \text{if tree } i \text{ in tree list } T_l \text{ was dead} \\ 0 & \text{otherwise} \end{cases} \tag{2.3}$$

Other features of riparian forests could be added to a tree list in a similar manner, if desired. The tree lists T_l defining a management option for the simulation years y_l, $l = 0, 1, 2, \ldots, Y$, may be obtained from a sequence of measurements on actual stands or they may be obtained from forest stand simulators such as the forest vegetation simulator (FVS) (Donnelly, 1997) or Organon (Hann et al., 1997).

To assign different management options to the buffer partitions within the one acre managed riparian area some additional notation for the management options is necessary. Let N_{options} be the number of available management options. For each management option o, $o = 1, 2, \ldots, N_{\text{options}}$, there exists a sequence of simulation years y_{ol}, $l = 0, 1, 2, \ldots, Y_o$, and a sequence of associated tree lists T_{ol}. Each tree list T_{ol} contains $N_{T_{ol}}$ trees $T_{oli} = [N_{oli}, D_{oli}^{\text{dbh}}, H_{oli}, S_{oli}, I_{oli}^{\text{leave}}]^T$, representing $N_{ol} = \sum_{i=1}^{N_{T_{ol}}} N_{oli}$ TPA for management option o and simulation year y_{ol}.

All management options were assumed to have the same management time interval $\Delta = y_{oY_o} - y_{o0}$, $o = 1, 2, \ldots, N_{\text{options}}$, spanning the time from the initial simulation year y_{o0} to the simulation management horizon of y_{oY_o}. Time intervals associated with the simulation years were also assumed to be synchronized across all management options, so that the time interval δ_l between simulation times $y_{o\,l-1}$ and y_{ol} were equal for all management options, $\delta_l = y_{ol} - y_{o\,l-1}$, $o = 1, 2, \ldots, N_{\text{options}}$. With these assumptions, only a single sequence of simulation years, y_l, $l = 0, 1, 2, \ldots, Y$, was needed for all management options.

2.3 Riparian management scenarios

A *riparian management scenario* was defined by specifying the partition of a one acre riparian buffer, as described in Section 2.1, an assignment of riparian management options to each of the management zones defined by the partition, and a procedure for constructing tree lists $\hat{T}_l$ corresponding to the simulation years y_l, $l = 0, 1, 2, \ldots, Y$ using the management zones and their respective canonical tree lists from each of the management options. The tree lists $\hat{T}_l$ for a riparian management scenario were constructed on a proportional basis, determined by the areas of the management zones, using the canonical tree lists assigned to each management zone for each simulation year y_l. The constructed tree lists were assumed to be representative of stand conditions that could occur for the management scenario, given the management options assigned to the management zones of the riparian buffer for each simulation year y_l.

Let $I_k = [B_{k-1}, B_k]$, $k = 1, 2, \ldots, K$, identify the management zones defined by a partition of the one acre riparian buffer, let f_k be the fraction of an acre represented by the management zone I_k, and let $o = O(k)$ be a function that returns the index o, $o \in \{1, 2, \ldots, N_{\text{options}}\}$, of the management option assigned to the management zone I_k. Define $\text{TL}(O(k), f_k, y_l)$ to be a function that returns a representative tree list derived from the management option $O(k)$ that was assigned to management zone I_k, representing that management option on the fraction f_k of the one acre buffer, $0 < f_k \leq 1$, for the simulation year y_l. A complete description of the function $\text{TL}(O(k), f_k, y_l)$ is given in Section 2.4.

A representative tree list for a management scenario having K management zones was constructed for each simulation year y_l, $l = 0, 1, 2, \ldots, Y$, in two steps. First, a representative tree list was obtained for the simulation year y_l and the management options $O(k)$ assigned to each management zone $k = 1, 2, \ldots, K$ using Equation 2.4

$$\hat{T}_{lk} = \text{TL}(O(k), f_k, y_l) \tag{2.4}$$

based on the fraction of the one acre riparian buffer represented by the management zone. The tree lists for each management zone k and simulation year y_l each contain $N_{\hat{T}_{lk}}$ trees $\hat{T}_{lki} = [\hat{N}_{lki}, \hat{D}^{\text{dbh}}_{lki}, \hat{H}_{lki}, \hat{S}_{lki}, \hat{I}^{\text{leave}}_{lki}]^T$. Second, the tree lists for each management zone $\hat{T}_{lk}$ in a simulation year y_l were merged to create the management scenario tree lists for each of the simulation years y_l as in Equation 2.5.

$$\begin{aligned} \hat{T}_l &= \{\hat{T}_{l1}, \hat{T}_{l2}, \ldots, \hat{T}_{lK}\} \\ &= \{\hat{T}_{l11}, \ldots, \hat{T}_{l1N_{\hat{T}_{l1}}}, \hat{T}_{l21}, \ldots, \hat{T}_{l2N_{\hat{T}_{l2}}}, \hat{T}_{lK1}, \ldots, \hat{T}_{lKN_{\hat{T}_{lK}}}\} \end{aligned} \tag{2.5}$$

The tree list $\hat{T}_l$ constructed for a management scenario may also be written as in Equation 2.6, where $N_{\hat{T}_l} = \sum_{k=1}^{K} N_{\hat{T}_{lk}}$ is the number of trees in the tree list $\hat{T}_l$, if explicit reference to the management zones I_k is not necessary.

$$\hat{T}_l = \{\hat{T}_{l1}, \hat{T}_{l2}, \ldots, \hat{T}_{l\,N_{\hat{T}_l}}\} \tag{2.6}$$

As for the management options, multiple management scenarios are desired. Let $N_{\text{scenarios}}$ be the number of management scenarios, and let K_m, $m = 1, 2, \ldots, N_{\text{scenarios}}$, be the number of management zones $I_{mk} = [B_{mk-1}, B_{mk}]$, $k = 1, 2, \ldots, K_m$, defined by a partition of the one acre riparian buffer for management scenario m. Each management zone I_{mk} represents a fraction f_{mk} of the one acre riparian buffer, and the function $o = O(m, k)$ identifies the management option $o \in \{1, 2, \ldots, N_{\text{options}}\}$ assigned to management zone I_{mk} for management scenario m. Tree lists representing the one acre riparian buffer for a management scenario m were constructed for each management zone k, $k = 1, 2, \ldots, K_m$, as before, using Equation 2.4 with $O(k)$ and f_k replaced by $O(m, k)$ and f_{mk} as in Equation 2.7.

$$\hat{T}_{mlk} = \text{TL}(O(m, k), f_{mk}, y_l) \tag{2.7}$$

The tree list $\hat{T}_{mlk}$ is then the tree list for management scenario m and simulation year y_l, representing the trees in management zone k derived from the canonical tree list $T_{O(m,k)\,l}$ for the management option $O(m, k)$ and simulation year y_l. A tree list $\hat{T}_{ml}$ constructed for management scenario m and simulation year y_l would then be obtained by merging the tree lists $\hat{T}_{mlk}$ for each management zone to get $\hat{T}_{ml} = \{\hat{T}_{ml1}, \hat{T}_{ml2}, \ldots, \hat{T}_{mlK_m}\}$.

2.4 Generating representative tree lists: The function TL

Consider a riparian management scenario having K management zones I_k with assigned management options $O(k)$, $k = 1, 2, \ldots, K$. The function $\mathrm{TL}(O(k), f_k, y_l)$ was used to generate a representative tree list $\hat{T}_{lk}$ for simulation year y_l, representing the trees on the fraction f_k of the one acre riparian buffer accounted for by management zone I_k from the canonical tree list $T_{O(k)\,l}$ for the management option $O(k)$ assigned to that management zone. The function $\mathrm{TL}(O(k), f_k, y_l)$ generates a representative tree list by randomly sampling, with replacement, individual trees from a canonical tree list $T_{O(k)\,l}$ based on the number of trees represented by the tree list, $N_{O(k)\,l}$, and the fraction f_k of the one acre riparian buffer accounted for by management zone I_k. The specific procedures and assumptions used within the function $\mathrm{TL}(O(k), f_k, y_l)$ to generate a representative tree list follow.

Let $T_{O(k)\,l}$ be the canonical tree list containing $N_{T_{O(k)\,l}}$ trees for the management option $O(k)$ assigned to management zone I_k for simulation year y_l, and let f_k be the fraction of the area represented by the management zone I_k. To simplify the description of the function $\mathrm{TL}(O(k), f_k, y_l)$ each tree $T_{O(k)\,li}$ in the canonical tree list $T_{O(k)\,l}$ for management option $O(k)$ was assumed to represent exactly one tree, that is, $N_{O(k)\,li} = 1$ for $i = 1, 2, \ldots, N_{T_{O(k)\,l}}$, and therefore $N_{O(k)\,li} = N_{T_{O(k)\,l}}$.

A tree list $T' = \{T'_1, T'_2, \ldots, T'_{N'_T}\}$ containing $N_{T'}$ trees having TPA values N'_i was expanded into a tree list $T = \{T_1, T_2, \ldots, T_{N_T}\}$ containing N_T trees, where $N_T \geq N_{T'}$, and each tree T_i represented exactly one tree within the simulated riparian area using the following tree list expansion algorithm. For each tree T'_i in T', let $N^{\mathrm{Int}} = \lfloor N'_i \rfloor$, where $\lfloor x \rfloor$ returns the largest integer less than or equal to x. If N^{Int} and N'_i were equal, then N'_i represented a whole number of trees, so add N^{Int} copies of tree T'_i to the tree list T, assigning a value of one to the TPA value for each of the replicated trees. If $N^{\mathrm{Int}} < N'_i$, then there was a fractional tree represented, so add $N^{\mathrm{Int}} + 1$ copies of tree T'_i to the tree list T, assigning a value of one to the TPA values for the first N^{Int} of the replicated trees and a TPA value of $N'_i - N^{\mathrm{Int}}$ to the last replicated tree. The number of trees contained in the tree list T is $N_T = \sum_{i=1}^{N_{T'}} \lceil N'_i \rceil$, where $\lceil x \rceil$ returns the smallest integer greater than or equal to x. The number of trees represented by the expanded tree list T is equal to the number of trees represented by the original tree list T', that is $\sum_{i=1}^{N_T} N_i = \sum_{i=1}^{N_{T'}} N'_i$, which includes all trees having fractional TPA values.

Given a canonical tree list $T_{O(k)\,l}$ containing trees representing exactly one TPA within a one acre riparian buffer area for a simulation year y_l, and f_k, the fraction of the one acre riparian buffer represented by management zone I_k, a representative tree list $\hat{T}_{lk}$ was constructed by assuming a strict definition of proportional representation. The definition of proportional representation used required each distinct category of tree, for example, leave tree or snag, within a canonical tree list $T_{O(k)\,l}$ to be represented in the constructed tree list $\hat{T}_{lk}$ based on the fraction f_k of the riparian acre represented by management zone I_k. Tree species was not considered as defining categories within this context. The proportional representation of tree species within a management zone was accounted for by the random sampling of trees within each category contained in the canonical tree list $T_{O(k)\,l}$.

Two categories of trees were recognized within the canonical tree lists that were defined in Section 2.2 for each simulation year y_l: leave trees and all other trees. When generating a representative tree list $\hat{T}_{lk}$ for management zone I_k using the canonical tree list $T_{O(k)\,l}$ for the management option $O(k)$ assigned to that management zone, both categories of tree need to be represented according to the fraction f_k of the one acre riparian buffer comprising the management zone I_k. Let $N_{O(k)\,l}$ be the number of TPA represented by the canonical tree list $T_{O(k)\,l}$. Define $T^{\text{leave}}_{O(k)\,l}$ to be the tree list containing the leave trees occurring in the tree list $T_{O(k)\,l}$, with $N^{\text{leave}}_{O(k)\,l}$, representing the number of leave trees in the tree list $T_{O(k)\,l}$, and let $T^{\text{other}}_{O(k)\,l}$ be the tree list containing the other, or non-leave, trees occurring in the tree list $T_{O(k)\,l}$, where $N^{\text{other}}_{O(k)\,l}$ is the number of other, or non-leave, trees occurring in the tree list $T_{O(k)\,l}$. Leave trees in a tree list $T_{O(k)\,l}$ were identified by an indicator $I^{\text{leave}}_{O(k)\,li}$, $i = 1, 2, \ldots, N_{O(k)\,l}$, having a value of one for leave trees, and a value of zero otherwise. The number of leave trees was computed using the values of the leave tree indicator as in Equation 2.8.

$$N^{\text{leave}}_{O(k)\,l} = \sum_{i=1}^{N_{O(k)\,l}} I^{\text{leave}}_{O(k)\,li} \tag{2.8}$$

The number of other, or non-leave, trees was then $N^{\text{other}}_{O(k)\,l} = N_{O(k)\,l} - N^{\text{leave}}_{O(k)\,l}$. Either of the tree lists $T^{\text{leave}}_{O(k)\,l}$ or $T^{\text{other}}_{O(k)\,l}$, or both, may be empty for a particular simulation year y_l.

Proportional representation of each category of tree within a tree list $\hat{T}_{lk}$ required that $\hat{N}^{\text{leave}}_{lk} = \text{Int}(f_k \cdot N^{\text{leave}}_{O(k)\,l})$ leave trees and $\hat{N}^{\text{other}}_{lk} = \text{Int}(f_k \cdot N^{\text{other}}_{O(k)\,l})$ other, or non-leave, trees be included. By rounding the numbers of representative trees using the function $\text{Int}(x)$, it was possible to obtain $\hat{N}^{\text{leave}}_{lk} = 0$ or $\hat{N}^{\text{other}}_{lk} = 0$, if the fraction of representative trees was less than $\frac{1}{2}$, causing a rounding down to zero. If a rounding to zero were to occur, then one tree from that category should be present in the representative tree list $\hat{T}_{lk}$. Therefore, if $\hat{N}^{\text{leave}}_{lk} = 0$ and $N^{\text{leave}}_{O(k)\,l} > 0$ a value of one was assigned to the representative number of leave trees $\hat{N}^{\text{leave}}_{lk} = 1$, or if $\hat{N}^{\text{other}}_{lk} = 0$ and $N^{\text{other}}_{O(k)\,l} > 0$, then a value of one was assigned to the representative number of other, or non-leave, trees $\hat{N}^{\text{other}}_{lk} = 1$. This was done to guarantee that at least one tree would be selected if the number of trees represented on the fraction of the riparian acre was not zero.

Finally, the representative tree list $\hat{T}_{lk}$ for simulation year y_l and management zone I_k was generated by randomly selecting, with replacement, the appropriate number of trees from each category of tree within the canonical tree list $T_{O(k)\,l}$ for management scenario $O(k)$ and simulation year y_l, and then merging them together. Clearly, other categories of tree, for example, standing dead trees or snags, could readily be included and used with the procedures described, if desired.

2.5 A managed riparian buffer simulation model

A representative tree list $\hat{T}_{ml}$ generated for management scenario m and simulation year y_l provides only one instantiation of the tree lists that are possible, given the canonical tree lists $T_{O(k)\,l}$ for the management options $O(k)$ assigned to the management zones I_k, $k = 1, 2, \ldots, K_m$, and hence only a single set of values for its measurable characteristics, for example, quadratic mean diameter (QMD), average height (H), volume per acre, basal area per acre (BA). Such a tree list can, therefore, only provide a small part of the information relating to the set of possible values for those characteristics. If the distribution of values or the potential range of variability is desired for a characteristic, or set of characteristics, a single estimate of its value, or their values, for a management option m and simulation year y_l is simply not sufficient.

To characterize the variability in, and distributions of, the forest characteristics for one acre managed riparian buffers the simulation approach previously defined was implemented, and allows multiple, nested management zones to be defined relative to a stream, and the application of a different management option within each management zone. The presentation of the algorithm for the simulations was simplified by defining the function $G = G(T)$ to return a value, or vector of values, for the characteristic or characteristics of the managed riparian forest that were of interest for a particular tree list T, for example the TPA, QMD, average height, or basal area per acre. Defining N_S to be the number of simulation trials, and letting

$s = 1, 2, \ldots, N_S$ index the trials, the algorithm used in the managed riparian buffer simulation model is defined by the following steps.

1. For each management scenario m, simulation year y_l, and simulation trial s generate a representative tree list $\hat{T}_{mls}$. This was done in three steps.
    (a) Generate the representative tree lists $\hat{T}_{mlsk} = \mathrm{TL}(O(m,k), f_{mk}, y_l)$, based on the tree list $T_{O(m,k)\,l}$ for the management option $O(m,k)$ applied to each management zone I_{mk}, $k = 1, 2, \ldots, K_m$ for simulation year y_l and simulation trial s.
    (b) Augment the tree lists $\hat{T}_{mlsk}$ for each management zone I_{mk} with additional information, such as distances from a stream for each tree, if desired. The additional information, if any, may depend on the particular issues being addressed by a simulation.
    (c) Merge the trees from the tree lists $\hat{T}_{mlsk}$ obtained for each management zone I_{mk} into a single tree list $\hat{T}_{mls} = \{\hat{T}_{mls1}, \hat{T}_{mls2}, \ldots, \hat{T}_{mlsK_m}\}$.
2. Compute the desired value or vector of values from each tree list $\hat{T}_{mls}$ for each management scenario m, simulation year y_l, and simulation trial s, $G_{mls} = G(\hat{T}_{mls})$.
3. Compute a statistical summary or a distribution of the desired characteristic, or characteristics,using the values G_{mls} from the simulation trials, for example the mean, $\bar{G}_{ml}$, and standard deviation, SD_{ml}, using Equation 2.9 and Equation 2.10, respectively.

$$\bar{G}_{ml} = \frac{1}{N_S} \sum_{s=1}^{N_S} G_{mls} \tag{2.9}$$

$$\mathrm{SD}_{ml} = \sqrt{\frac{1}{N_S - 1} \sum_{s=1}^{N_S} \left(G_{mls} - \bar{G}_{ml}\right)^2} \tag{2.10}$$

Chapter 3

Application

The managed riparian buffer simulation model was used to simulate the development of managed riparian forest stands in western Washington State. The characteristics of interest were the structural development of managed riparian forests produced by using multiple management zones within a one acre riparian buffer. Of particular interest was the potential for multiple zone managed riparian buffers to produce structural characteristics associated with older forests and their ability to supply LWD to streams. Both issues of these issues are of major importance for privately owned managed riparian forests in Washington State (FFR, 1999, WFPB, 2001).

Over $N_{\text{options}} = 100$ management options were defined and used to generate canonical tree lists for the management zones within the modeled multi-zone riparian buffers. The management options included several no treatment options, 50, 70, 80, and 100 year rotations, and a number of multiple thinning treatments designed to accelerate tree growth and promote the development of mature forest structures and several treatments that included underplantings to promote a multi-story canopy. Using these management options $N_{\text{scenarios}} = 400$ riparian management scenarios were defined, each having from one to three management zones within the 170 ft wide one acre riparian buffer.

Given the large number of management options and management scenarios, only six of the management scenarios are considered here, with their respective management options, to demonstrate the managed riparian buffer simulation model and to highlight some of the issues involved in modeling riparian buffers. The management options used to define the selected management scenarios are described in the next section, Section 3.1, followed by descriptions of the selected management scenarios in Section 3.2. The potential to produce functional instream LWD is known to depend on stream size, so six stream size classes were specified for the application, with corresponding minimum functional LWD log dimensions, length and diameter at the point of near bank stream intersection, and they are defined in Section 3.3. Potentially avaialable LWD was then broken down by stream size class for each of the selected managemant scenarios. Trajectories for the stand characteristics TPA, QMD, average height (H), BA, and the potential for LWD production were produced for each of the selected management scenarios using a 140 year time span and a five year time interval. The procedures used to compute the stand attributes are described in Section 3.4.

Table 3.1: Management option descriptions.

Option Name	Option Description
UPLAND1	Plant 400 Douglas-fir TPA, thin to 180 TPA at 20 years, clearcut at 50 years.
25HOLD	Plant 400 Douglas-fir TPA, thin to 180 TPA at 20 years, thin to 60 TPA at 50 years, thin to 25 TPA at 70 years and hold.
25HOLDU	Same as 25HOLD with an under-planting of 300 TPA, 50% Douglas-fir and 50% western red cedar, at 70 years.
10LEAVE	Plant 400 Douglas-fir TPA, thin to 180 TPA at 20 years, clearcut at 50 years, leaving 10 TPA over 12 inches DBH or the largest 10 TPA.
20LEAVE	Plant 400 Douglas-fir TPA, thin to 180 TPA at 20 years; clearcut at 50 years, leaving 20 TPA over 12 inches DBH or the largest 20 TPA.
NOACTION	Plant approximately 500 TPA with no further action.

3.1 Management option descriptions

The management options that were used to define the selected riparian management scenarios are described in Table 3.1. For each management option, a 140 year management horizon was used, with five year intervals between successive canonical tree lists, giving $Y = 28$ simulation years $y_1 = 5, y_2 = 10, \ldots, y_{28} = 140$ and the initial year $y_0 = 0$ for the initial condition, for a total of 29 canonical tree lists for each managemtn option. The canonical tree lists T_{ol} used to represent each management option o, $o = 1, 2, \ldots, N_{\text{options}}$ and simulation year y_l, $l = 1, 2, \ldots, 28$ were generated using the Landscape Management System (LMS) (McCarter et al., 1998, McCarter, 2001) and the SMC variant of the ORGANON forest growth model version 6.0 (Hann et al., 1997), ORGANON-SMC, which was calibrated for western Washington using the database maintained by the Stand Management Cooperative (SMC) at the University of Washington (Chappell et al., 1988, Maguire et al., 1991). Version 6.0 of the ORGANON-SMC growth model is the defacto model required by Washington State for riparian forest analyses and was used to develop the desired future conditions assessment model worksheet (DFC Model) that is required to be used for forest practices applications in riparian areas.

The canonical tree lists for all of the management options described here were based on LMS projections from initial tree lists T_{o0}, $o = 1, 2, \ldots, N_{\text{options}}$, that were derived from a single tree list that represented an actual riparian stand, the base stand. The base stand was a 20 year old, 100% pure stand of Douglas-fir, that contained 472 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 therefore a 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, and 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.

3.1.1 Management option initial tree lists

Initial canonical tree lists T_{o0} for each management option $o = 1, 2, \ldots, N_{\text{options}}$ and simulation year $y_0 = 0$ were derived from the tree list representing the base stand. The initial canonical tree list for the high density no action management option, NOACTION, was simply the tree list for the base stand. The initial canonical tree lists for the management options containing a thinning treatment 20 years ofter planting were derived from the base stand by assuming that the initial tree lists were obtained after the thinning event, since the age of the base stand was 20 years and the initial thinning for all management options having a thinning occurred at age 20. The initial canonical tree lists for these management options were, then, obtained by thinning the base stand from 472 TPA to the desired stand density, 180 TPA for the management options presented here from below. All subsequent thinnings were also from below, taking the smallest trees first, and were performed by LMS during the 140 year projections of the management options.

3.1.2 Management option treatments

The management options may be broken down into three basic types: fixed term rotations with one or more thinning treatments and periodic clearcuts with various leave tree requirements, thin and hold strategies with one or more thinning treatments, and no action strategies. Thinning, clearcut harvesting, and planting were assumed to be the only treatments available for the management options. Thinning treatments were assumed to be from below, taking the smallest trees first. Multiple thinning events were permitted for a managment option. Clearcuts were assumed to remove all standing, live trees leaving 2 trees per acre that were assumed to meet the green tree retention requirements for western Washington (WFPB, 2001). The leave trees were required to have DBH values that were at least 10 inches. The leave trees were not harvested, but were carried forward throughout the 140 year management time horizon. If a leave tree died, it was replaced at the next clearcut with another leave tree.

A 10 year regeneration period was assumed to follow a clearcut and subsequent planting, with the additional assumption that there was no mortality within the first 10 years after planting. The stand regeneration event, then, occurred 10 years after a clearcut, with the stand density for the 10 year old regeneration being equal to the desired planting density of 400 TPA for the selected management options. There is, therefore, an instantaneous change in stand density and average tree size 10 years after a clearcut, rather than a gradual change in the number of trees taller than breast height and the average tree size. The regeneration was based on a canonical stand of 10 year old Douglas-fir trees used for regeneration within LMS. The 2 trees per acre retained after a clearcut were also required by LMS to project the management options having clearcuts through the first simulation year, five years after the clearcut, to reach the simulation year 10 years later where the stand regeneration was assumed to occur. Given the five year interval between simulation years, a five year regeneration period would have been ideal, but a canonical stand of five year old Douglas-fir trees was not available for Douglas-fir regeneration within LMS at the time these analyses were performed.

The no action management option, NOACTION, was based on a high density planted Douglas-fir stand with a planting density of approximately 500 TPA. This managment option was intended to represent the development of young overstocked, managed riparian stands. This management option should not be considered to represent a typical, naturally occurring, riparian condition. It is a stand condition designed to promote rapid initial tree growth, with an intent to thin early so that rapid tree growth can be maintained throughout a rotation, maximizing the early production of wood volume.

Several of the management options represented fixed term rotations culminating in a clearcut. There were a number of variations based on a 50 year rotation, e.g., UPLAND1, with different initial planting densities, thinning strategies, and final harvest times that were intended to represent a range of typical practices used to manage upland, or non riparian, stands. Several long rotation management options based on the use of biodiversity pathways (Carey et al., 1999) to promote the development of biologically relevant forest structures and habitat while sustaining economic viability were also created.

A number of management options were designed to rapidly produce mature forest structures, particularly an overstory containing relatively large trees at moderate to low stand densities. These were the thin and hold strategies, that employed a fixed number of thinning treatments to accelerate tree growth and produce larger trees for an overstory, after which there would be no further active management, the hold part of the strategy. Thin and hold strategies were used for a variety of final stand densities, including 25 TPA for the management options 25HOLD and 25HOLDU, which had their final thinnings 70 years after planting. The management option 25HOLDU included an underplanting of 300 TPA, 50% Douglas-fir and 50% western red cedar, at 70 years after planting to allow the simulation of the development of an understory.

Two management options, 20LEAVE and 10LEAVE, were designed to represent management strategies that were compatible with the guidelines specified by management Option 2 of the FFR (FFR, 1999, WFPB, 2001) for management of the inner and outer zones, respectively, of a riparian buffer as define by the the washington state forest practices rules. The FFR defined three nested buffer zones along potentially fish bearing streams: a 50 ft core no harvest buffer directly adjacent to the stream, an inner zone where timber harvest was allowed subject to restrictions ensuring the development of desired future conditions based on the combined core and inner zones, and an outer zone, where, again, a number of harvest restrictions are applied.

The total buffer width was determined by the site potential tree height and can vary from 90 ft to 200 ft based on the Douglas-fir site class (King, 1966), with lower site classes having narrower buffer widths. The inner zone extends from the outer edge of the core zone to either 67% or 75% of the total buffer width depending on stream size (FFR, 1999, Ehlert and Mader, 2000, Fairweather, 2001, WFPB, 2001). Further distinctions are made in the rules based on stream size, allowing streams with bank-full widths less than 10 ft to have narrower inner and outer buffer zones than streams with bank-full widths greater than 10 ft.

Management under Option 2 of the FFR permits harvest in the inner zone provided that 1) the site has a high productivity, Douglas-fir site classes I, II, and III (King, 1966); 2) no harvest occurs within 80 ft of a stream, for streams having a bank-full width less than 10 ft, or within 100 ft of a stream, for streams having a bank-full width greater than 10 ft, except for site class III for the larger streams; 3) at least 20 TPA having DBH values greater then 12 inches were left in the inner zone after harvest; and 4) harvest proceeds toward the stream from the outer edge of the inner zone. Management for site class III under Option 2 is not permitted for streams with a bank-full width greater than 10 ft since the outer edge of the inner zone would be closer to the stream than the 100 ft no cut constraint. If 20 TPA having DBH values greater than 12 inches were unavailable, then the largest trees available were left to meet the requirement. Management option 20LEAVE was designed to meet the leave tree requirements for the harvestable portion of the inner zone under Option 2 of the FFR.

Management under the FFR permits harvest in the outer zone provided that 20 TPA having DBH values greater then 12 inches were left in the zone after harvest. Under Option 2 of the FFR, if the site had a high productivity, Douglas-fir site classes I, II, and III (King, 1966), and the core and inner zones were projected to exceed the requirements necessary to meet the desired future conditions, then additional harvest was permitted in the outer zone. The additional harvest was limited to the over run, relative to the desired future conditions, and required that at least 10 TPA having DBH values greater then 12 inches must still be left. Management option 10LEAVE was designed to meet the leave tree requirements for outer zone management under Option 2 of the FFR. For this analysis the combined inner and core zones were assumed to exceed the requirements necessary to meet the desired future conditions to allow the maximum harvest.

None of the management options presented so far directly account for ingrowth or natural regeneration and the development of an understory that would be expected to occur within a managed riparian stand over time. The 25HOLDU management option, via its underplanting to produce an understory, should partially address the issue of ingrowth or natural regeneration, and may provide some insight into their potential impacts on stand development, structure, and function within a riparian zone.

Table 3.2: Selected management scenario descriptions.

	Partition Description					
Scenario Name	K_m	k	$B_{m\,k-1}$	$B_{m\,k}$	Acres	Management Option
Alt 03	3	1	0 ft	25 ft	0.147	NOACTION
		2	25 ft	80 ft	0.324	25HOLDU
		3	80 ft	170 ft	0.529	UPLAND1
Alt 03 No Under Plant	3	1	0 ft	25 ft	0.147	NOACTION
		2	25 ft	80 ft	0.324	25HOLD
		3	80 ft	170 ft	0.529	UPLAND1
No Action	1	1	0 ft	170 ft	1.000	NOACTION
Alt 49	2	1	0 ft	30 ft	0.147	NOACTION
		2	30 ft	170 ft	0.853	UPLAND1
FFR Option 2 $<$ 10 ft	3	1	0 ft	80 ft	0.471	NOACTION
		2	80 ft	113 ft	0.194	20LEAVE
		3	113 ft	170 ft	0.335	10LEAVE
FFR Option 2 $>$ 10 ft	3	1	0 ft	100 ft	0.588	NOACTION
		2	100 ft	113 ft	0.076	20LEAVE
		3	113 ft	170 ft	0.335	10LEAVE

3.2 Management scenario descriptions

Over $N_{\text{scenarios}} = 400$ management scenarios were designed and simulated for the 140 year management horizon defined by the management options. The management scenarios contained between $K_m = 1$ and $K_m = 3$ management zones. 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, and a reach along a stream of 256.2 ft. All management options 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 also assumed within each defined management zone.

Six of the management scenarios were selected to demonstrate the managed riparian buffer simulation model and to highlight some of the issues involved in riparian buffer management. Descriptions of these six management scenarios and their respective management zones appear in Table 3.2.

The management scenarios, Alt 03 and Alt 03 No Under Plant were designed to have a no treatment bank stability zone directly adjacent to a stream, an intermediate zone intended to rapidly produce larger trees and a diverse size structure that would be representative of older or mature riparian forests, and an economic management zone that was considered to be outside the zone of riparian influence. The underplanting for management scenario Alt 03 was used to directly represent the production of a multilayered canopy, as well as to address the potential impact of ingrowth or natural regeneration on the stand development and functions that the adjacent forest provide to a stream, for example LWD or shade.

The two FFR management scenarios, FFR Option 2 $<$ 10 ft and FFR Option 2 $>$ 10 ft, were both designed based on the current rules for riparian forest management in western Washington State (FFR, 1999, WFPB, 2001) for Douglas-fir site class II (FFR, 1999, WFPB, 2001). When designing the two FFR based management scenarios several assumptions were made. First, the combined core and inner zones were assumed to exceed the desired future conditions requirements allowing the maximum harvest in the outer zone. Given the relatively large no harvest zone, the inherent uncertainty in forest stand projections over long time periods, and the rapidly decreasing influence trees far from a stream have on riparian function, particularly the potential production of LWD (McDade et al., 1990, Van Sickle and Gregory, 1990), this seemed reasonable. Second, was the assumption that the leave trees for the harvestable portion of the inner management zone were randomly, uniformly, distributed within the zone. This assumption differs from the requirements of the FFR in that the trees left in the inner and outer management zones were to be the trees closest to a stream.

The random placement of trees within the harvestable portion of the FFR inner management zone should have minimal impact on the analyses for several reasons. First, the harvestable region in the inner management zone is only 33 ft wide, representing approximately 0.20 acres, or approximately 4 TPA out of the 20 TPA required to be left as leave trees. Given the rapid decline in riparian influence for trees far from a stream, the contribution of this small number of trees to stream function from this distance would be expected to be negligible, even if located as close to a stream as possible within this portion of the inner management zone. Second, trees in the harvestable portion of the FFR inner management zone that were large enough to contribute to stream function would typically be large enough to contribute wherever they were located within this zone, given its relatively narrow width.

The final two management scenarios represent a no action alternative for the entire riparian buffer, No Action, and a 30 ft no harvest zone adjacent to a stream, Alt 49. The no management scenario was based on the NOACTION management option as the young, overstocked stand conditions represented by this management option were considered to be representative of the conditions on a significant portion of the managed riparian forests in western Washington State, in part due to the legacy of young, dense stands planted in riparian zones prior to the passage of the FFR. The management scenario based on the 30 ft no harvest zone was included for comparative purposes, as it provides a potential lower bound for LWD production from the set of management scenarios and is comparable to the rules prior to the FFR.

3.2.1 Management scenario tree lists

To support the simulation of the potential production of instream LWD for managed riparian buffers the basic simulated tree vectors were augmented by adding coordinates for the position of each tree within a management zone, giving distances from and locations along a stream in step 1(b) of the simulation algorithm described in Section 2.5. Simulated tree lists $\hat{T}_{mlsk}$ for management scenario m, simulation year y_l, simulation trial s, and management zone k were, therefore, composed of tree vectors

$$\hat{T}_{mlski} = [\hat{N}_{mlski}, \hat{D}^{\text{dbh}}_{mlski}, \hat{H}_{mlski}, \hat{S}_{mlski}, \hat{d}_{mlski}, \hat{r}_{mlski}]^T,$$

where $\hat{N}_{mlski}$ was the number of trees represented by simulated tree i, $\hat{D}^{\text{dbh}}_{mlski}$ was the DBH of simulated tree i, $\hat{H}_{mlski}$ was the height of simulated tree i, $\hat{S}_{mlski}$ was the species of simulated tree i, $\hat{r}_{mlski}$ was the reach position or location along a stream for simulated tree i, and $\hat{d}_{mlski}$ was the distance from a stream for simulated tree i. Values for $\hat{N}_{mlski}$, $\hat{D}^{\text{dbh}}_{mlski}$, $\hat{H}_{mlski}$, and $\hat{S}_{mlski}$ were based on the randomly selected trees from the management options $O(m,k)$ assigned to the management zones I_{mk} for management scenario m and simulation trial s. Values for the distance from a stream $\hat{d}_{mlski}$ and reach location $\hat{r}_{mlski}$ for each tree i were randomly generated from uniform distributions $U(B_{m\,k-1}, B_{mk})$ and $U(0, 256.2)$, respectively, within each management zone, following the assumption that trees were uniformly distributed within their management zones.

Table 3.3: 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) $D_{\text{min}}^{\text{lwd},j}$	Minimum LWD length (ft) $L_{\text{min}}^{\text{lwd},j}$
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

3.3 Stream size classes and minimum functional LWD dimensions

The sizes and number of functional LWD logs are known to vary with stream size (Bilby and Ward, 1989, 1991, Fox, 2001, Welty et al., 2002), with larger and fewer logs providing stream functions such as pool formation in larger streams than in smaller streams. Six stream size classes for the simulations 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). Minimum dimensions for functional LWD logs for each stream size class were based on Beechie and Sibley (1997), Beechie et al. (2000) and Fox (2001), with adjustments.

Let $J = 6$ 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, $D_{\text{min}}^{\text{lwd},j}$ and $L_{\text{min}}^{\text{lwd},j}$, respectively, that are necessary for a log to be considered a functional LWD log for that stream class. Values for the stream bank-full widths and the minimum dimensions for functional LWD logs are presented in Table 3.3. The minimum dimensions of functional LWD logs for stream classes E and F are equal to the minimum dimensions for potential LWD logs, and they may be used to estimate the total, potentially available LWD volumes and piece counts.

3.4 Computing stand characteristics from the simulated tree lists

The stand characteristics computed for each management scenario m, simulation year y_l, and simulation trial s using the augmented simulated tree lists $\hat{T}_{mls}$ were the TPA, QMD, average height (H), basal area per acre (BA) and estimates of expected values for the volume and piece count of potentially available LWD (ALWD) and potentially available functional LWD(AFLWD) (Gehringer, 2004) for the simulated riparian buffers. When computing the stand characteristics only trees having a DBH value of at least 4 inches were used. Computed values represent the one acre riparian buffer zone. The indicator function $I(\hat{D}_i^{\text{dbh}}, 4)$ given by Equation 3.1 was used to select the trees having DBH values that were at least 4 inches.

$$I(x, y) = \begin{cases} 1 & \text{if } x \geq y \\ 0 & \text{otherwise} \end{cases} \tag{3.1}$$

For simplicity in describing the formulas used to compute the stand characteristics, let $\hat{T}$ represent an augmented tree list for some management scenario m, simulation year y_l, simulation trial s. The tree list contains tree vectors $\hat{T}_i = [\hat{N}_i, \hat{D}_i^{\text{dbh}}, \hat{H}_i, \hat{S}_i, \hat{d}_i, \hat{r}_i]^T$, describing the characteristics of each tree, where $\hat{N}_i$ was the number of trees represented by simulated tree i, $\hat{D}_i^{\text{dbh}}$ was the DBH of simulated tree i, $\hat{H}_i$ was the height of simulated tree i, $\hat{S}_i$ was the species of simulated tree i, $\hat{d}_i$ was the distance from a stream for simulated tree i, and $\hat{r}_i$ was the reach position along a stream for tree i.

The TPA, QMD, average height, and BAfor trees having DBH values of at least 4 inches were computed using the formulas in Equation 3.2 through Equation 3.5.

$$G^{\text{TPA}}(\hat{T}) = \sum_{i=1}^{N_{\hat{T}_i}} \hat{N}_i \cdot I(\hat{D}_i^{\text{dbh}}, 4) \tag{3.2}$$

$$G^{\text{BA}}(\hat{T}) = k \cdot \sum_{i=1}^{N_{\hat{T}}} \hat{N}_i \cdot (\hat{D}_i^{\text{dbh}})^2 \cdot I(\hat{D}_i^{\text{dbh}}, 4) \tag{3.3}$$

$$G^{\text{H}}(\hat{T}) = \frac{\sum_{i=1}^{N_{\hat{T}}} \hat{H}_i \cdot \hat{N}_i \cdot I(\hat{D}_i^{\text{dbh}}, 4)}{\sum_{i=1}^{N_{\hat{T}}} \hat{N}_i \cdot I(\hat{D}_i^{\text{dbh}}, 4)} \tag{3.4}$$

$$G^{\text{QMD}}(\hat{T}) = \left(\frac{\sum_{i=1}^{N_{\hat{T}}} \hat{N}_i \cdot (\hat{D}_i^{\text{dbh}})^2 \cdot I(\hat{D}_i^{\text{dbh}}, 4)}{\sum_{i=1}^{N_{\hat{T}}} \hat{N}_i \cdot I(\hat{D}_i^{\text{dbh}}, 4)} \right)^{\frac{1}{2}} \tag{3.5}$$

where $k = \frac{\pi}{4 \cdot 144} = 0.005454$. Estimates of mean expected values for ALWD and AFLWD volume and piece counts were computed using functions $G^{\text{ALWD}}(\hat{T})$ and $G^{\text{AFLWD}}(\hat{T})$ based on the LWD availability model described in Gehringer (2004).

Trajectories for the management scenario simulation results were based on the time since planting. This was computed by adding the initial age of the base stand used to derive the initial management scenario tree lists, 20 years, to the time difference between the simulation year y_l and the initial simulation year $y_0 = 0$, $(y_l - y_0) + 20$, $l = 0, 1, 2, \ldots, 28$.

Chapter 4

Results

Results from the simulations for the selected set of management scenarios are presented using mean values and standard deviations computed using values obtained for each stand characteristic from each of the $N_S = 100$ simulation trials. The simulation trials for each management scenario were run independently. All of the stand characteristics for management scenario m, simulation year y_l, and simulation trial s were computed using the same simulated tree list $\hat{T}_{mls}$, including the expected values for ALWD and AFLWD volume and piece counts for each of the six stream size classes. The expected values for the potentially available LWD were, therefore, not derived from independent simulations for each stream size class.

The results consist of figures showing trajectories of the stand characteristics for the selected management scenarios, mean values plus or minus one standard deviation for each scenario and simulation year, and tables giving numerical values of the stand characteristics for the selected management scenarios, again, mean values with standard deviations, for times since planting of 20, 40, 80, 120, and 160 years, or the simulation years $y_0 = 0$, $y_4 = 20$, $y_{12} = 60$, $y_{20} = 100$, and $y_{28} = 140$. The results are presented in three parts, beginning with the trajectories for the stand structure characteristics in Section 4.1, followed by the trajectories for the expected potentially available LWD in Section 4.2. The ALWD and AFLWD results are presented as volume and piece count trajectories over time in Section 4.3 and Section 4.4, respectively. The ALWD trajectory results were then broken down by functional size for the different stream size classes in Table 3.3 to get results for AFLWD. The ALWD and AFLWD results are presented only for stream size classes A through D, as the results for stream size classes E and F were indistinguishable from those for stream size class D.

4.1 Stand structure trajectories

The simulated mean stand density trajectories for the selected management scenarios, based on trees having a DBH of at least 4 inches, are plotted in Figure 4.1, with stand density values for times since planting of 20, 40, 80, 120, and 160 years given in Table 4.1. Initial stand densities, 20 years after planting, ranged from a value of 227.0 TPA for the Alt 03, Alt 03 No Under Plant, and Alt 49 management scenarios to 472.0 TPA for the No Action management scenario, with intermediate stand densities of 323.0 TPA and 358.0 TPA for the FFR Option 2 $<$ 10 ft and FFR Option 2 $>$ 10 ft management scenarios, respectively. Final stand densities ranged from 103.8 TPA for the Alt 03 No Under Plant management scenario to 148.8 TPA for the Alt 49 management scenario. The somewhat narrow range in final stand densities, however, contains a variety of stand structures ranging from a uniform stand of 160 year old trees, obtained from the No Action

Table 4.1: Mean TPA trajectory results for trees having a DBH of at least 4 inches and times since planting of 20, 40, 80, 120, and 160 years for the selected management scenarios. Standard deviations are in parentheses. Variability is present at 160 years due to the presence of trees from a planting or stand regeneration having DBH values that were less than 4 inches.

	Time since planting (years)				
Scenario Name	20	40	80	120	160
Alt 03	227.0	207.0	161.7	194.0	143.9
	(0.0)	(0.0)	(3.7)	(0.0)	(8.1)
Alt 03 No Under Plant	227.0	207.0	137.0	130.0	103.8
	(0.0)	(0.0)	(0.0)	(0.0)	(7.5)
No Action	472.0	388.0	239.0	179.0	144.0
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Alt 49	237.0	212.0	192.0	183.0	148.8
	(0.0)	(0.0)	(0.0)	(0.0)	(8.4)
FFR Option 2 < 10 ft	323.0	276.0	205.0	179.0	140.8
	(0.0)	(0.0)	(0.0)	(0.0)	(6.7)
FFR Option 2 > 10 ft	358.0	300.0	214.0	179.0	144.6
	(0.0)	(0.0)	(0.0)	(0.0)	(5.8)

management scenario, to a stand having a multistoried canopy near a stream with a mixture of large 160 year old trees and smaller 70 year old trees in the understory for the Alt 03 management scenario, to a stand having a 160 year old trees within 30 ft of a stream with 10 year old trees in the remainder of the riparian acre for the Alt 49 management scenario. The variability at 160 years for all scenarios except No Action was caused by the presence of trees with DBH values that were less than 4 inches from the planted stand regeneration occurring after the harvest at 150 years.

The complete 140 year mean stand density trajectories in Figure 4.1 clearly show the harvests and the 10 year regeneration cycle for the five active management scenarios. The high degree of synchronization among the active management scenarios resulted from the timing of the primary harvest events which occurred on a 50 year cycle after planting. The effect of the underplanting 70 years after planting for management scenario Alt 03 is clearly evident, raising the stand density by more than 100 TPA over a period of 20 years and creating an understory. The Alt 49 and Alt 03 No Under Plant management scenarios have the lowest post-harvest stand densities, with the Alt 03 No Under Plant scenario maintaining the lowest stand densities throughout the 140 year management horizon. By 120 years after planting, the stand density for the underplanted treatment in management scenario Alt 03 exceeds, or is approximately equal to, the stand density for the FFR management scenarios, maintaining this relationship until the end of the 140 year management horizon. The stand density for the FFR Option 2 > 10 ft management scenario generally exceeded that of the FFR Option 2 < 10 ft scenario throughout the 140 year management horizon, with an initial difference of 35 TPA and declining to a value of 3.7 TPA by 160 years since planting. By 120 years after planting the two FFR scenarios are maintaining almost identical levels of stand density, with the differences being noticed only post harvest, where it is 15 TPA. The post harvest differences also declined, from values after the initial harvest of approximately 35 TPA to 15 TPA after the final harvest.

The simulated mean QMD trajectories for the selected management scenarios, based on trees having a DBH of at least 4 inches, are plotted in Figure 4.2, with QMD values for times since planting of 20, 40, 80, 120, and 160 years given in Table 4.2. Initial QMD values, 20 years after planting, ranged from a low value of 7.6 inches for the No Action management scenario, with the Alt 03, Alt 03 No Under Plant, and Alt 49 scenarios having essentially equal values of 8.8 inches, and values of 8.1 inches and 8.1 inches for the

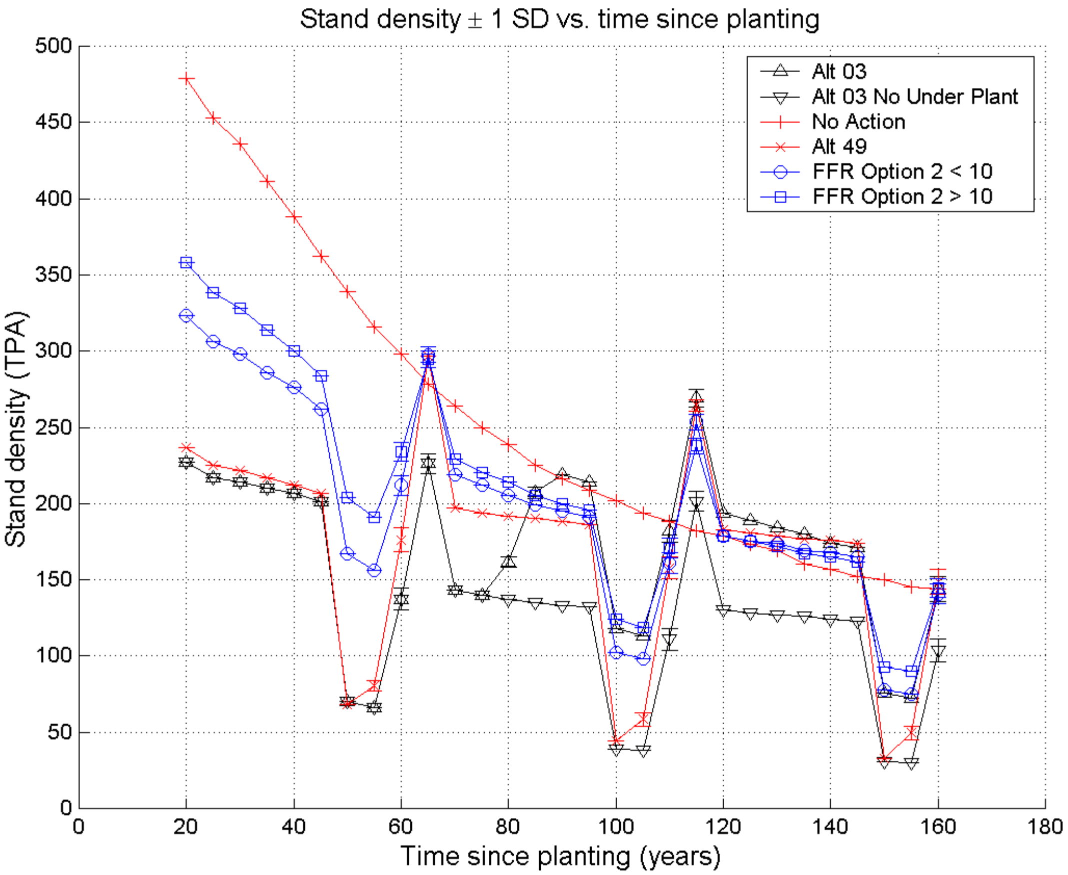

Figure 4.1: Mean TPA trajectory results for trees having a DBH of at least 4 inches. Variability is present following planting or regeneration due to the presence of trees having DBH values that were smaller than 4 inches.

Table 4.2: Mean QMD trajectory results (inches) for trees having a DBH of at least 4 inches and times since planting of 20, 40, 80, 120, and 160 years for the selected management scenarios. Standard deviations are in parentheses.

	Time since planting (years)				
Scenario Name	20	40	80	120	160
Alt 03	8.8 (0.1)	13.3 (0.2)	13.6 (0.3)	13.0 (0.4)	14.9 (0.7)
Alt 03 No Under Plant	8.8 (0.1)	13.3 (0.2)	14.7 (0.3)	14.9 (0.4)	16.6 (1.0)
No Action	7.6 (0.1)	11.3 (0.2)	16.6 (0.4)	20.3 (0.6)	23.4 (0.7)
Alt 49	8.7 (0.1)	13.2 (0.2)	14.2 (0.2)	12.8 (0.4)	11.6 (0.6)
FFR Option 2 < 10 ft	8.1 (0.1)	12.3 (0.1)	14.8 (0.3)	15.4 (0.5)	16.9 (0.8)
FFR Option 2 > 10 ft	8.0 (0.1)	12.0 (0.2)	15.3 (0.3)	16.6 (0.5)	18.3 (0.7)

FFR Option 2 < 10 ft and FFR Option 2 > 10 ft management scenarios, respectively. Final QMD values ranged from 11.6 inches for the Alt 49 management scenario to 23.4 inches for the No Action management scenario. Smaller mean QMD values for the active management scenarios were due to including the smaller trees when computing the QMD value for the entire one acre riparian buffer. These values should, therefore, not be assumed to provide an indication of the uniform sizes of trees within their respective buffers. The variability of the QMD values increased throughtout the 140 year management horizon due to the increased variability in tree sizes, due to harvesting and planting or regeneration and stand differentiation.

The complete 140 year QMD trajectories in Figure 4.2 clearly show the harvests and the 10 year regeneration cycle for all of the active management scenarios. The high degree of synchronization among the active management scenarios resulted from the timing of the primary harvest events which occurred every 50 years after planting. The effect of the underplanting 70 years after planting for management scenario Alt 03 is clearly evident, significantly lowering the mean QMD value, relative to all other management scenarios, and in particular relative to scenario Alt 03 No Under Plant, until the next harvest through the creation of an understory. Further the mean QMD values for the Alt 03 management scenario remained lower than that for the Alt 03 No Under Plant management scenario from the time of the underplanting at age 70 until the end of the 140 year management horizon. The Alt 03 No Under Plant management scenario produced the largest trees, as indicated by the mean QMD values during the 10 year regeneration intervals. The mean QMD values for the Alt 49 and the No Action management scenarios generally bracketed, from below and above, respectively, the range of mean QMD values for the remaining management scenarios, except for the regeneration periods where the Alt 03 No Under Plant management scenario provided the upper bound. The mean QMD values for the two FFR scenarios are very similar throughout the 140 year time period, with the largest differences occurring as the post harvest regeneration grows in, producing trees greater than 4 inches DBH.

The simulated mean average height trajectory results for the selected management scenarios, based on trees having a DBH of at least 4 inches, are plotted in Figure 4.3, with average height values for times since planting of 20, 40, 80, 120, and 160 years given in Table 4.3. Initial mean average height values, 20 years after planting, were very similar, and ranged from a low value of 48.5 ft for the No Action management scenario to a high value of 50.8 ft for the Alt 03 and Alt 03 No Under Plant management scenarios, with intermediate

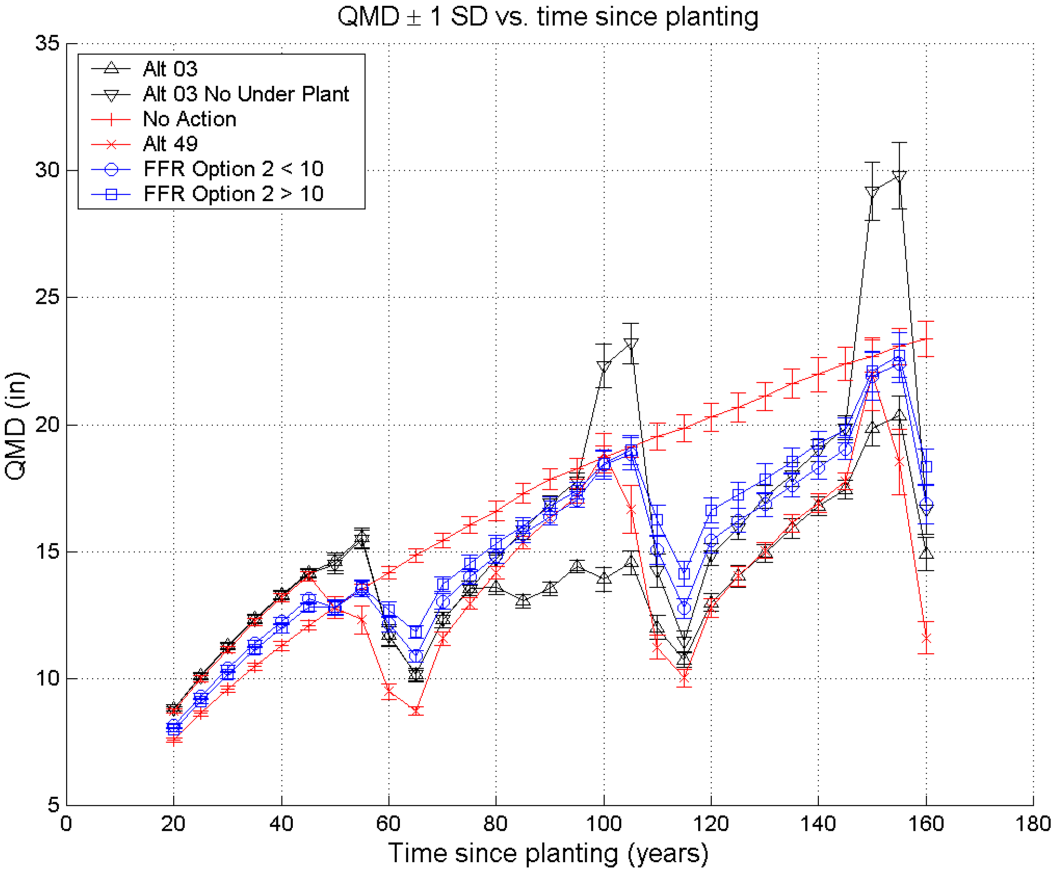

Figure 4.2: Mean QMD trajectory results for trees having a DBH of at least 4 inches.

Table 4.3: Mean average height trajectory results (ft) for trees having a DBH of at least 4 inches and times since planting of 20, 40, 80, 120, and 160 years for the selected management scenarios. Standard deviations are in parentheses.

	Time since planting (years)				
Scenario Name	20	40	80	120	160
Alt 03	50.8 (0.3)	91.5 (0.5)	83.3 (1.5)	79.2 (0.6)	82.7 (3.6)
Alt 03 No Under Plant	50.8 (0.3)	91.1 (0.5)	94.1 (0.7)	80.1 (0.9)	68.4 (3.4)
No Action	48.5 (0.2)	85.8 (0.6)	130.4 (1.3)	156.2 (1.7)	175.3 (1.8)
Alt 49	50.7 (0.3)	91.2 (0.5)	88.0 (0.7)	70.0 (0.7)	52.5 (1.9)
FFR Option 2 < 10 ft	49.5 (0.2)	88.4 (0.5)	105.1 (0.9)	100.6 (1.1)	100.1 (4.0)
FFR Option 2 > 10 ft	49.2 (0.2)	87.6 (0.5)	111.4 (1.0)	113.2 (1.2)	114.9 (3.9)

values of 50.7 ft, 49.5 ft, and 49.2 ft for the Alt 49, FFR Option 2 < 10 ft, and FFR Option 2 > 10 ft management scenarios, respectively. Final mean average height values ranged from 52.5 ft for the Alt 49 management scenario to 175.3 ft for the No Action management scenario. Smaller mean average height values for the active management scenarios were due to including the smaller trees when computing the values for the entire one acre riparian buffer. The smallest mean average height values were expected for the Alt 49 management scenario since it had the largest harvestable area and, hence, the greatest number of smaller trees at any point in time after the first harvest. The small average heights at 160 years since planting are due to the inclusion of the regeneration trees planted ten years earlier after the harvest in the active management scenarios, and, therefore, should not be interpreted as a uniform tree size withn the buffer areas.

The complete 140 year average height trajectories in Figure 4.3 clearly show the harvests and the 10 year regeneration cycle for all of the active management scenarios. The high degree of synchronization among the active management scenarios resulted from the timing of the primary harvest events which occurred every 50 years after planting. The effect of the underplanting 70 years after planting for management scenario Alt 03 is clearly evident, significantly lowering the mean average height value, relative to all other management scenarios until the next harvest through the creation an understory. Further, the mean average height values for the Alt 03 management scenario remained lower than that for the Alt 03 No Under Plant management scenario from the time of the underplanting at age 70 until the end of the 140 year management horizon. The Alt 03 No Under Plant management scenario produced the largest trees, as indicated by the mean average height values during the 10 year regeneration intervals. The mean average heights for the No Action management scenario were very similar to those for the other management scenarios during the 10 year regeneration intervals occurring after the harvests at 50, 100, and 150 years, showing little differentiation at 100 years, and only slightly more at 150 years. The exception was for the Alt 03 management scenario which had significantly smaller mean average height values due to the trees planted to produce an understory. The mean average height values for the Alt 49 and the No Actionmanagement scenarios generally bracketed, from below and above, respectively, the range of mean average height values for the remaining management scenarios, except for the regeneration periods where the Alt 03 No Under Plant management scenario provided the upper bound.

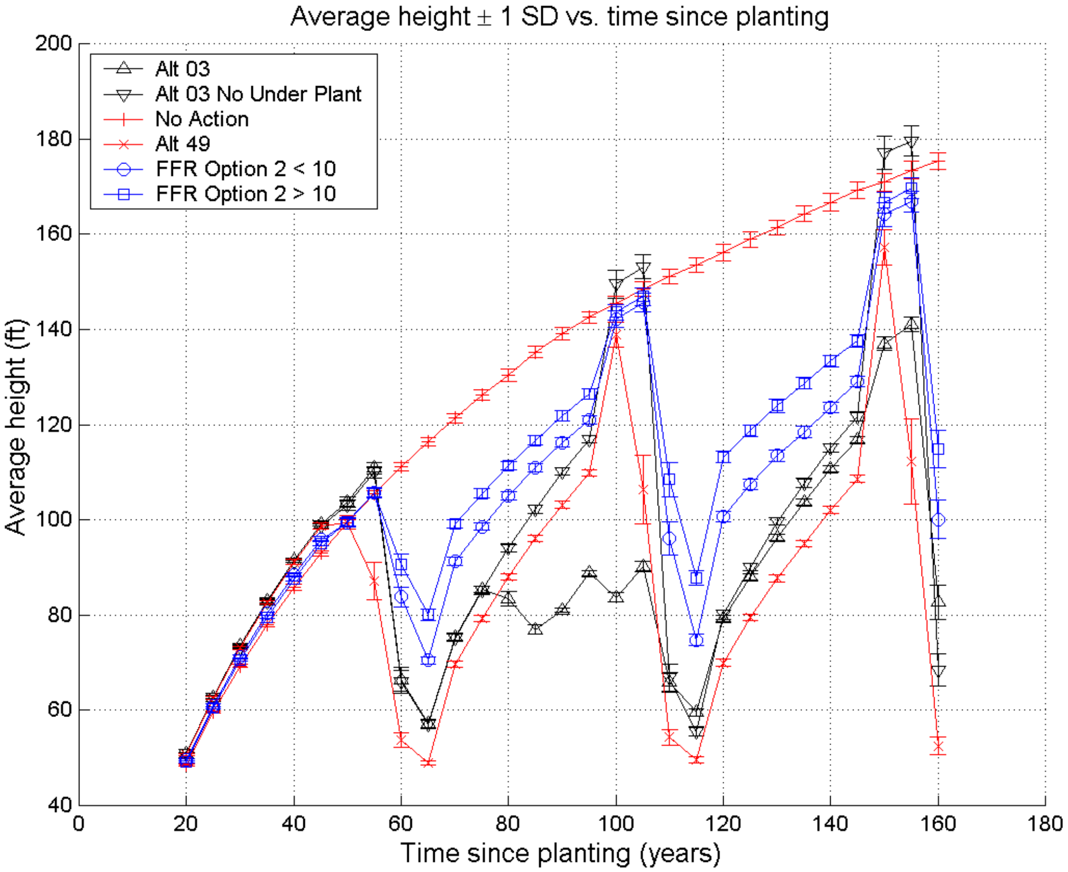

Figure 4.3: Mean average height trajectory results for trees having a DBH of at least 4 inches.

Table 4.4: Mean BA trajectory results ($\mathrm{ft}^2\mathrm{ac}^{-1}$) for trees having a DBH of at least 4 inches and times since planting of 20, 40, 80, 120, and 160 years for the selected management scenarios. Standard deviations are in parentheses.

	Time since planting (years)				
Scenario Name	20	40	80	120	160
Alt 03	95.8 (1.9)	199.5 (4.8)	163.4 (6.4)	178.8 (9.7)	174.0 (12.0)
Alt 03 No Under Plant	95.8 (2.0)	198.4 (4.8)	161.3 (6.0)	157.1 (9.2)	156.8 (15.7)
No Action	150.0 (4.0)	269.9 (8.6)	359.4 (16.1)	402.5 (21.8)	429.3 (26.0)
Alt 49	98.3 (2.1)	201.1 (5.2)	210.5 (7.1)	163.1 (9.2)	109.2 (10.5)
FFR Option 2 $<$ 10 ft	116.9 (2.9)	226.3 (5.4)	246.0 (9.9)	233.0 (14.9)	218.1 (16.7)
FFR Option 2 $>$ 10 ft	124.3 (2.2)	234.9 (6.6)	273.4 (11.4)	269.9 (15.9)	265.5 (19.3)

The simulated mean BA trajectories for the selected management scenarios, based on trees having a DBH of at least 4 inches, are plotted in Figure 4.4, with BA values for times since planting of 20, 40, 800, 120, and 160 years given in Table 4.4. Initial BA values, 20 years after planting, ranged from low values of 95.8 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for the Alt 03 and Alt 03 No Under Plant management scenarios, to a high value of 150.0 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for the No Action management scenario, with intermediate values of 98.3 $\mathrm{ft}^2\mathrm{ac}^{-1}$, 116.9 $\mathrm{ft}^2\mathrm{ac}^{-1}$, and 124.3 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for the Alt 49, FFR Option 2 $<$ 10 ft, and FFR Option 2 $>$ 10 ft management scenarios, respectively. The FFR management scenarios had higher initial BA values since they had the larger no harvest zones adjacent to the stream, comprising 0.471 acres, and 0.588 acres, respectively. For all active managment scenarios, the managed zones were thinned to the same initial density, 180 TPA. Final BA values ranged from 109.2 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for the Alt 49 management scenario to 429.3 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for the No Action management scenario, with intermediate values of 174.0 $\mathrm{ft}^2\mathrm{ac}^{-1}$ and 156.8 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for scenarios Alt 03 and Alt 03 No Under Plant, respectively, and values of 218.1 $\mathrm{ft}^2\mathrm{ac}^{-1}$ and 265.5 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for FFR Option 2 $<$ 10 ft and FFR Option 2 $>$ 10 ft, respectively.

Maximum BA values for the active management scenarios occurred just prior to the last harvest event at 145 years since planting, having values ranging from 265.2 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for the Alt 03 No Under Plant management scenario to 345.9 $\mathrm{ft}^2\mathrm{ac}^{-1}$ for the FFR Option 2 $>$ 10 ft management option, with intermediate values of 283.9 $\mathrm{ft}^2\mathrm{ac}^{-1}$ 299.8 $\mathrm{ft}^2\mathrm{ac}^{-1}$ 326.6 $\mathrm{ft}^2\mathrm{ac}^{-1}$, respectively, for scenarios Alt 03, Alt 49, and FFR Option 2 $<$ 10 ft. The No Action management scenario had the largest BA value of 416.6 $\mathrm{ft}^2\mathrm{ac}^{-1}$ at that time.

The complete 140 year BA trajectories in Figure 4.4 clearly show the harvests and the 10 year regeneration cycle for all of the active management scenarios. The high degree of syncronicity among the active management scenarios is still readily apparent following the harvest events which occurred every 50 years after planting. The effect of the underplanting 70 years after planting for management scenario Alt 03 is also apparent, with the Alt 03 scenario producing larger BA values than the Alt 03 No Under Plant management scenario, by approximately 20 $\mathrm{ft}^2\mathrm{ac}^{-1}$, and maintaining the larger BA value from then on. The No Action management scenario produced the largest BA values throughout the entire 140 year management horizon. The Alt 49 scenario produced the smallest BA values for the first 20 years after a harvest event, with teh smallest values for the remaining 30 years between harvest events being produced by the Alt 03 and Alt 03 No Under Plant scenarios. The variability of BA values increased over time for all of the scenarios.

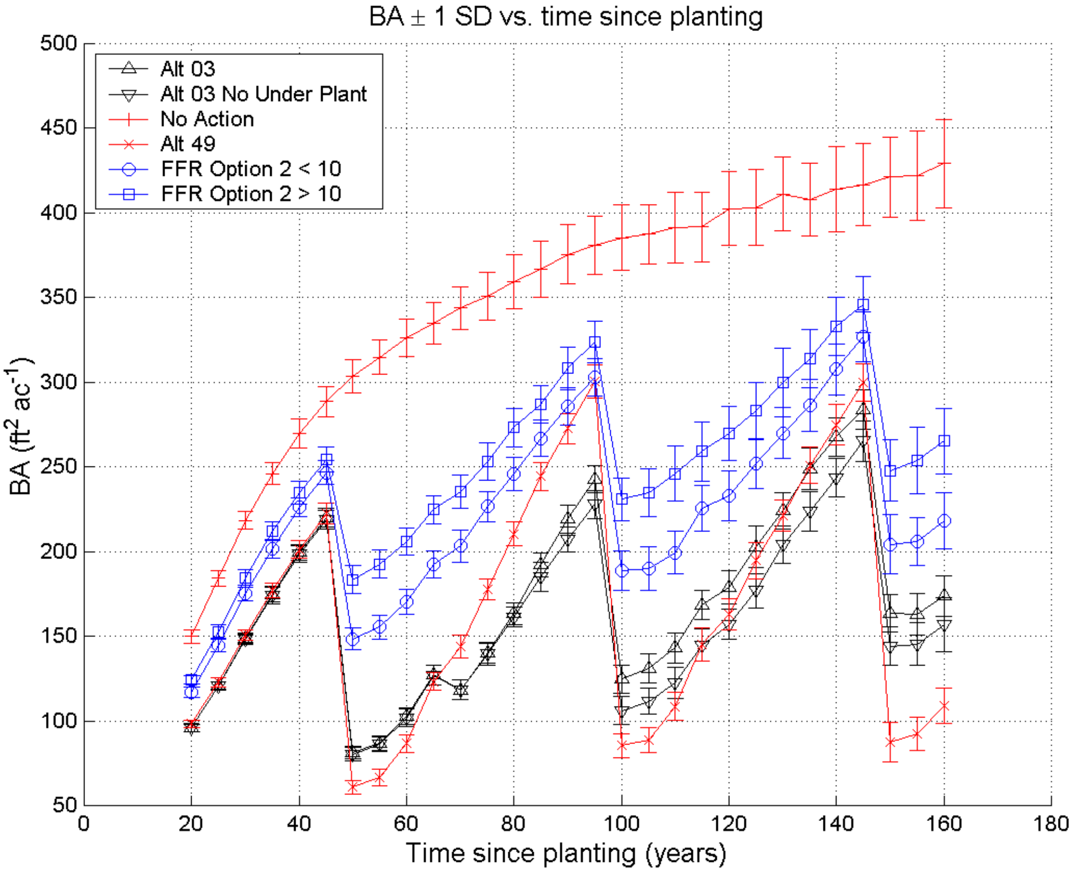

Figure 4.4: Mean BA trajectory results for trees having a DBH of at least 4 inches.

Table 4.5: Mean expected ALWD volume trajectory results ($ft^3 ac^{-1}$) for times since planting of 20, 40, 80, 120, and 160 years for the selected management scenarios. Standard deviations are in parentheses. Only trees having a DBH of at least 4 inches were considered.

	Time since planting (years)				
Scenario Name	20	40	80	120	160
Alt 03	99.0 (12.0)	627.3 (46.7)	1390.3 (149.9)	2128.1 (261.5)	2858.2 (320.4)
Alt 03 No Under Plant	99.0 (12.0)	615.4 (46.5)	1372.1 (121.4)	2212.5 (221.1)	3016.5 (392.1)
No Action	103.3 (18.1)	649.8 (80.7)	2065.3 (230.1)	3237.7 (417.4)	4224.1 (559.4)
Alt 49	101.6 (12.9)	633.1 (52.7)	1286.1 (158.2)	1771.5 (242.4)	1980.3 (296.8)
FFR Option 2 < 10 ft	103.6 (16.3)	666.9 (64.9)	2002.6 (182.3)	2953.5 (292.8)	3734.2 (420.0)
FFR Option 2 > 10 ft	103.8 (14.8)	652.3 (72.7)	2071.7 (220.0)	3166.2 (351.4)	4008.4 (409.5)

4.2 Potentially available LWD trajectories

4.3 LWD volume trajectories

Simulated mean ALWD, total potentially available LWD, volume trajectories for the selected management scenarios are plotted in Figure 4.5, with ALWD volumes for times since planting of 20, 40, 80, 120, and 160 years given in Table 4.5. The values were obtained using only trees having a DBH of at least 4 inches. The trajectories show that the potentially available functional LWD volume increased throughout the 140 year management horizon. The initial LWD availability, 20 years after planting, was approximately 100.0 $ft^3 ac^{-1}$ for all of the management scenarios, with Alt 03 and Alt 03 No Under Plant having initial ALWD volumes equal to 99.0 $ft^3 ac^{-1}$, with the remaining scenarios all having initial ALWD volumes in the range from 101.6 $ft^3 ac^{-1}$ to 103.8 $ft^3 ac^{-1}$. Potentially available LWD volume increased rapidly for all of the scenarios, producing final volumes of 2858.2 $ft^3 ac^{-1}$ and 3016.5 $ft^3 ac^{-1}$ for the Alt 03 and Alt 03 No Under Plant scenarios, 3734.2 $ft^3 ac^{-1}$ and 4008.4 $ft^3 ac^{-1}$ for the FFR Option 2 < 10 ft and FFR Option 2 > 10 ft scenarios, with minimum and maximum volumes of 1980.3 $ft^3 ac^{-1}$ and 4224.1 $ft^3 ac^{-1}$ for the Alt 49 and No Action scenarios, respectively. Note that the final ALWD volume for the Alt 03 scenario is less than that for the Alt 03 No Under Plant scenario, indicating that the establishment of an understory inhibited the production of available LWD volume. The variability of potentially available LWD volume increased as the volumes increased, but was consistently between 7% and 17% of the mean values.

The complete 140 year ALWD volume trajectories in Figure 4.5 shows the rapid increase in ALWD volumes and the differentiation in the volume trajectories caused by the management strategies of the selected scenarios. The trajectory for the Alt 49 management scenario decreases after the three harvest events at 50 years, 100 years, and 150 years, within the 140 year management horizon, showing the effects of the harvests on ALWD volume. Trajectories for the Alt 03 and Alt 03 No Under Plant scenarios show a small decrease following the first harvest at 50 years, a flattening at 70 years when the final thinning and underplanting occurred, but no indication of the two subsequent harvest events. The ALWD volume trajectories for the FFR Option 2 < 10 ft and FFR Option 2 > 10 ft management scenarios show no impacts from the harvest events and are essentially equivalent to the No Action scenario for the first 90 years after planting. The No Action and FFR scenarios produced more ALWD volume earlier than all of the other scenarios, beginning with the first harvest 50 years after planting. The No Action and FFR Option 2 $<$ 10 ft management scenarios began to differentiate approximately 90 years after planting, with the FFR Option 2 $>$ 10 ft scenario beginning to differentiate from the No Action scenario approximately 30 years later. While there was differentiation in the mean trajectories, the mean values were not statistically significantly different among these three scenarios: the mean values were well within 1.5 standard deviations of each other, regardless of the scenario. The Alt 03 and Alt 03 No Under Plant management scenarios produced trajectories that were quite similar, with no noticable differentiation. The ALWD volume trajectories for the No Action and Alt 49 management scenarios bracketed, above and below, the trajectories for the remaining scenarios.

The total potentially available LWD volume for each management scenario is comprised of LWD logs of varying sizes. The distribution of LWD log sizes for each management scenario is dependent on the state of stand development, the sizes of the trees in the riparian stand, and the locations of the trees relative to an adjacent stream. The distribution of LWD log sizes that could be produced by a riparian forest determines the amount of potentially available LWD that could be considered functional for a particular stream size, measured by bank-full width, with larger streams requiring larger LWD logs to provide instream function, such as pool formation. The potentially available LWD volumes partitioned by functional size class over the 140 year projections are provided in Figure 4.6. The minimum dimensions used for functional LWD were presented in Table 3.3. Only stream size classes A through D are presented as incremental amounts of LWD volume for stream classes E and F were negligible.

All of the selected management scenarios produced LWD logs that were of functional size for the stream size classes A through D (the increments for stream class D were too small to be seen given the scale of the graph). Comparing the AFLWD volume trajectories for the largest logs, stream size class A, the trajectories for the scenarios Alt 03, No Action, FFR Option 2 $<$ 10 ft, and FFR Option 2 $>$ 10 ft are all similar and produced nearly equivalent final mean LWD volume values. The Alt 03 scenario produced more AFLWD volume eariler for this functional LWD size class than the other three scenarios, as evidenced by the concave shape of its trajectory. The No Action and FFR scenarios have essentially identical trajectories for AFLWD in size class A, which was expected, since the large LWD logs must come from trees that are close to a stream, and these three scenarios all have a no harvest zone adjacent to a stream that is at least 80 ft wide. The Alt 49 scenario produced the smallest amounts of AFLWD volume for functional LWD size class A, consistent with its having the largest harvestable area, but it still produced approximately 50% of the volume produced by the four similar scenarios. The Alt 03 No Under Plant scenario produced the largest amounts of AFLWD volume for functional size class A, exceeding the volume produced by the Alt 03 scenario by approximately 50%, indicating that the underplanting inhibited the development of very large trees.

The increments in ALWD volume qualifying as functional for stream size class B dominated the potentially available LWD for this stream size class which also included the AFLWD volume from the largest size class, as well as being the size class contributing the most potentially functional LWD, except for the Alt 03 No Under Plant scenario. This is most obvious for the No Action, FFR Option 2 $<$ 10 ft, FFR Option 2 $>$ 10 ft, and Alt 49 scenarios. The AFLWD volume increments for the No Action, FFR Option 2 $<$ 10 ft, FFR Option 2 $>$ 10 ft, differ only in proportion to the size of their no harvest regions, with the increment for the No Action scenario greater than that for the FFR Option 2 $>$ 10 ft scenario, which was, in turn, greater than the increment for the FFR Option 2 $<$ 10 ft scenario. The increments for functional size class B for the Alt 03 scenario are greater than those for the Alt 03 No Under Plant scenario from, approximately, 120 years onward, while their functional LWD volumes for this stream size class were similar, indicating that the underplanted scenario produced more smaller trees that contributed to functional LWD, since comparable volumes for this stream size class were attained. The Alt 49 scenario produced increments of AFLWD volume that were comparable the those of the Alt 03 scenario for functional size class B, and the harvest events at 100 and 150 years clearly reduced the functional LWD volumes for this size class.

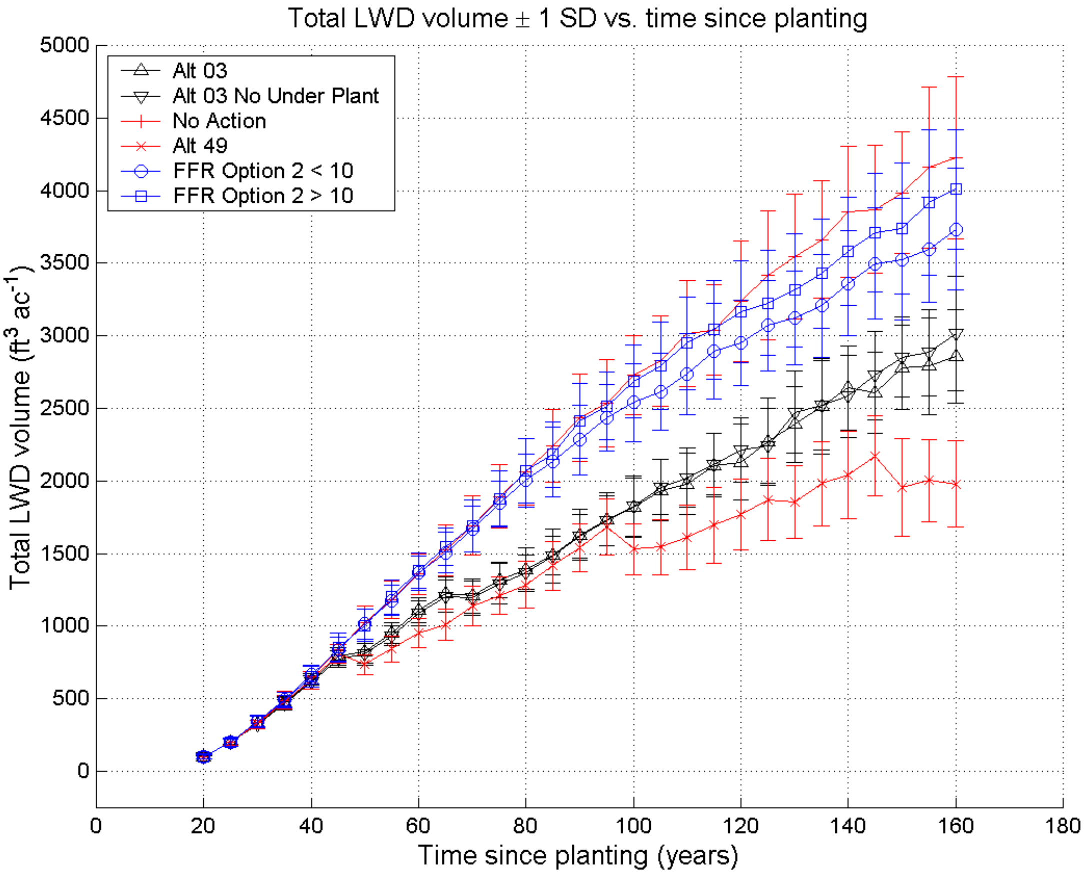

Figure 4.5: Mean expected ALWD volume trajectory results (ft^{3}ac^{-1}) for trees having a DBH of at least 4 inches.

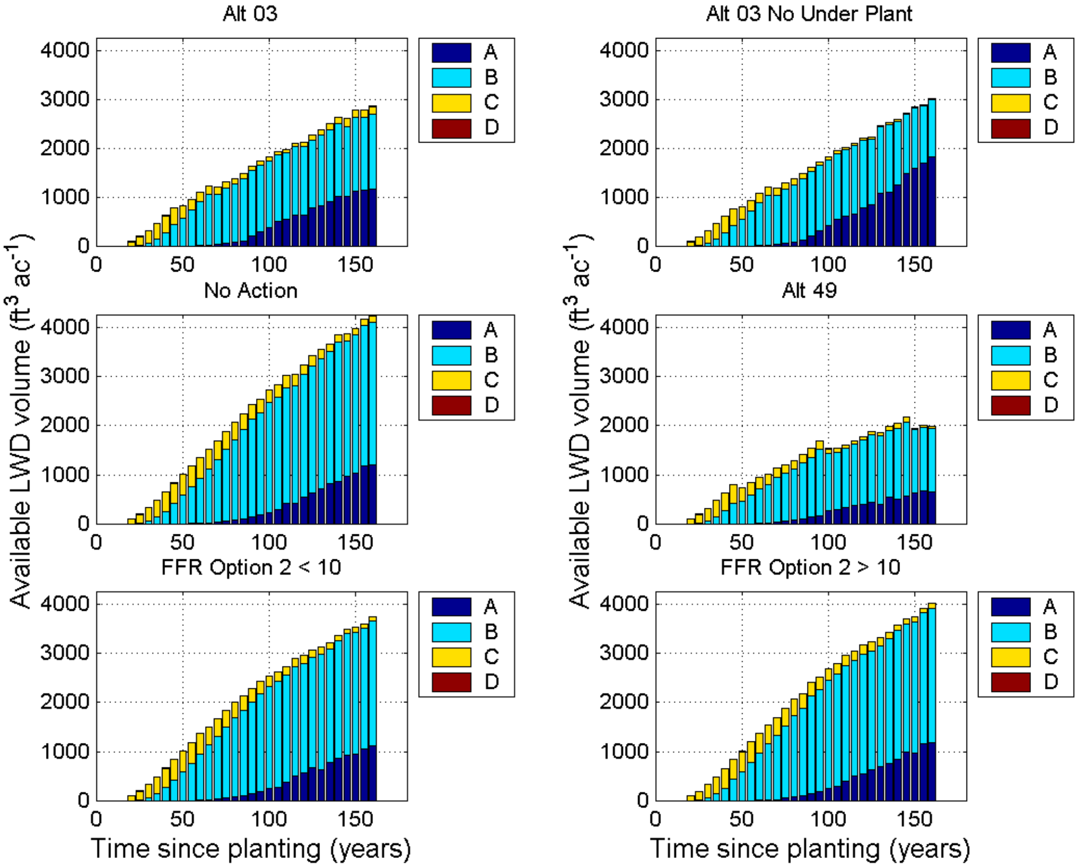

Figure 4.6: Mean expected ALWD volume breakdown by stream class ($\text{ft}^3\text{ac}^{-1}$) and trees having a DBH of at least 4 inches.

Table 4.6: Mean expected ALWD piece count trajectory results (n ac^{-1}) for times since planting of 20, 40, 80, 120, and 160 years for the selected management scenarios. Standard deviations are in parentheses. Only trees having a DBH of at least 4 inches were considered.

	Time since planting (years)				
Scenario Name	20	40	80	120	160
Alt 03	24.1 (1.5)	38.7 (1.0)	19.2 (0.2)	24.0 (1.1)	26.1 (0.5)
Alt 03 No Under Plant	24.1 (1.5)	38.3 (1.0)	19.4 (0.2)	15.5 (0.2)	13.3 (0.1)
No Action	24.5 (3.0)	47.2 (3.7)	49.9 (3.1)	45.8 (2.6)	42.1 (2.0)
Alt 49	24.7 (1.6)	40.3 (1.5)	26.5 (1.2)	16.6 (0.5)	12.8 (0.5)
FFR Option 2 $<$ 10 ft	25.0 (2.6)	47.9 (2.4)	42.8 (0.9)	34.4 (0.6)	28.5 (0.4)
FFR Option 2 $>$ 10 ft	24.8 (2.6)	47.5 (2.9)	47.6 (1.5)	39.4 (1.0)	33.3 (0.6)

Examining the volume increments for LWD qualifying as functional for stream size class C, there are, again, strong similarities among the No Action, FFR Option 2 $<$ 10 ft, and FFR Option 2 $>$ 10 ft management scenarios, where volumes from the small pieces increase and then decrease as the number of smaller trees declines over time. Visible in the increments for the Alt 49 scenario are the impacts of the harvest events at 50, 100 and 150 years and their subsequent reductions in AFLWD volume for functional size class C. The AFLWD increments for functional size class C for Alt 03 and Alt 03 No Under Plant scenarios are identical for the first 70 years, after which the AFLWD volume increments in this size class decline for the Alt 03 No Under Plant scenario as smaller trees disappear, while those for the Alt 03 scenario decline and then begin to increase as the understory trees became large enough to fall and reach the stream.

4.4 LWD piece count trajectories

The simulated mean ALWD piece count trajectories for the selected management scenarios and total potentially available LWD are plotted in Figure 4.7, with the ALWD piece counts for times since planting of 20, 40, 80, 120, and 160 years given in Table 4.6. The values were obtained using only trees having a DBH of at least 4 inches. The initial ALWD piece count availability, 20 years after planting, was approximately 24.1 pieces ac^{-1} for all of the selected management scenarios, indicating that there were no significant differences in the initial availability of LWD pieces. These were all similar since all of the selected management scenarios had similar initial tree size distributions and a 30 ft wide no harvest region directly adjacent to the stream, which provided the majority of the initial potentially available LWD. Given the initial average height and QMD values of approximately 50 ft and 8 inches for all of the selected scenarios, the average effective tree height was 35.4 ft, so only trees within, approximately, the first 35.4 ft of the stream could potentially contribute LWD.

The mean ALWD piece counts increased rapidly, achieving values ranging from a minimum of 40.3 pieces ac^{-1} for the Alt 49 management scenario to a maximum value of 47.5 pieces ac^{-1} for the No Action, FFR Option 2 $<$ 10 ft, and FFR Option 2 $>$ 10 ft management scenarios, with the Alt 03 and Alt 03 No Under Plant scenarios producing approximately 38.5 pieces ac^{-1}, by 40 years after planting. Final ALWD piece count values ranged from a low of 12.8 pieces ac^{-1} for the Alt 49 scenario to a high value of 42.1 pieces ac^{-1} for the No Action scenario, with values of 33.3 pieces ac^{-1} for the FFR Option 2 $>$ 10 ft scenario, 28.5 pieces ac^{-1} for the FFR Option 2 $<$ 10 ft scenario, 26.1 pieces ac^{-1} for the Alt 03 scenario, and 13.3 pieces ac^{-1} for the Alt 03 No Under Plant scenario. The final piece count value for the Alt 03 sceanrio is nearly double the final value for the Alt 03 No Under Plant scenario, with the underplanting being the only difference between the scenarios. Also notice that the final piece count value for the Alt 03 scenario is very similar to that of the FFR Option 2 $<$ 10 ft scenario.

The variability in the number of potentially available LWD pieces generally decreased throughout the 140 year management horizon for all of the selected management scenarios, except following a harvest or underplanting, when it would increase due to the greater number and size diversity of the trees present. The general decline in variability over time was caused by the presence of larger trees near a stream and the inclusion of small functional LWD logs in the totals. The latter reduced the influence of tree location for the larger trees, as well as allowing trees further from a stream to contribute ALWD pieces. The No Action management scenario maintained the greatest variability. This was due primarily to the fact that the other management scenarios left more trees preferentially near a stream, via narrower no harvest or minimum management zones near the stream, the most likely area to produce ALWD pieces, thereby reducing the tree size and distance variability near the stream, and hence reducing the variability of ALWD.

The complete 140 year ALWD piece count trajectories in Figure 4.7 show that the ALWD piece counts increased rapidly until the initial harvest 50 years after planting, after which the ALWD piece counts for the management scenarios with narrower no harvest regions declined. The trajectories for ALWD pieces increased to maximum values that occurred between 40 and 60 years after planting for all of the selected scenarios, after which the ALWD piece counts declined. The ALWD piece counts declined for the remainder of the 140 year management horizon, except for the Alt 03 and Alt 49management scenarios. These scenarios had increases in their ALWD piece counts following the underplanting for the Alt 03 management scenario, and following the the 50 year and 100 year harvest events, with a lags of 25 and 15 years, respectively. The initial decline in ALWD for the Alt 03, Alt 03 No Under Plant, and Alt 49 managemnet scenarios was a direct results of the harvest event at 50 years. The final thinning at 70 years for the Alt 03 and Alt 03 No Under Plant managemnt scenarios is also evident, and caused a further reduction in the ALWD piece counts. A small final reduction in the ALWD piece counts may be observed for the Alt 03 and FFR Option 2 $<$ 10 ft, scenarios after the final harvest event at 150 years, evidenced by the slightly steeper decline, and a small reduction may also be visible for the FFR Option 2 $>$ 10 ft at this time. The ALWD piece count trajectories for the No Action and Alt 49 management scenarios generally bracketed, above and below, the trajectories for the remaining scenarios, except for the times between 70 years and 100 years, where the Alt 03 and Alt 03 No Under Plant scenarios had the fewest ALWD pieces, and between 110 years and 150 years where the Alt 03 No Under Plant scenario had the fewest pieces.

The total number of potentially available LWD pieces for each management scenario is comprised of LWD logs of varying sizes. The distribution of LWD log sizes for each management scenario is dependent on the state of stand development, the sizes of the trees in the riparian stand, and the locations of the trees relative to an adjacent stream. The distribution of LWD log sizes that could be produced by a riparian forest determines the amount of potentially available LWD that could be considered functional for a particular stream size, measured by bank-full width, with larger streams requiring larger LWD logs to provide instream function, such as pool formation. The number of potentially potentially available LWD pieces partitioned by functional size class over the 140 year projections are provided in Figure 4.6. The minimum dimensions used for functional LWD were presented in Table 3.3. Only stream size classes A through D are presented as the incremental number of LWD pieces for stream classes E and F were negligible.

All of the selected management scenarios produced LWD logs that were of functional size for the stream size classes A through D. Comparing the AFLWD piece count trajectories for the largest logs, stream size

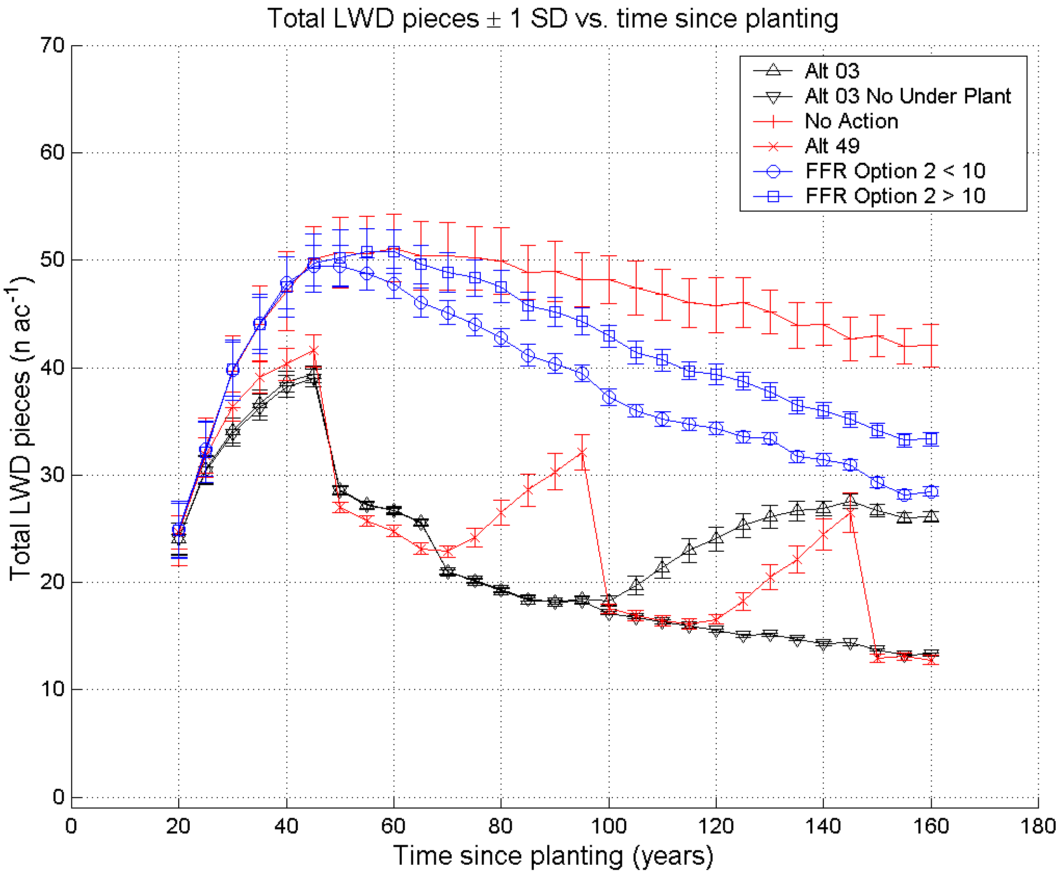

Figure 4.7: Mean expected ALWD piece count trajectory results (n ac^{-1}) for trees having a DBH of at least 4 inches.

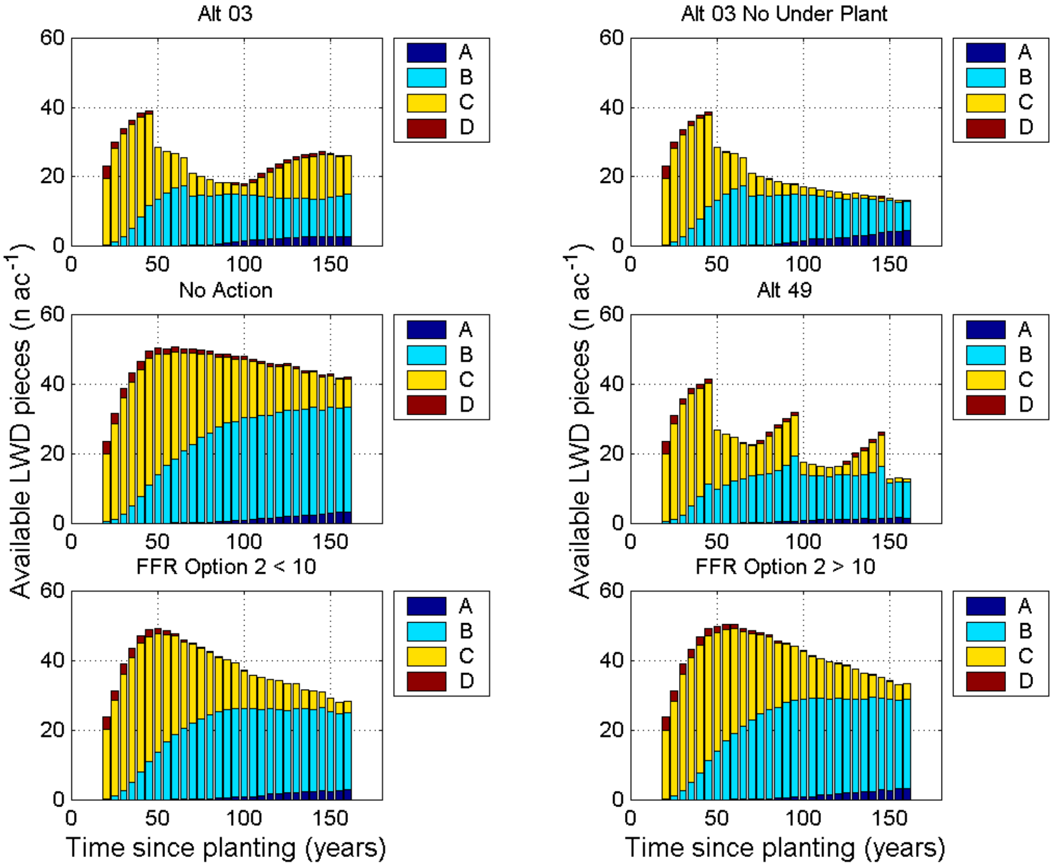

Figure 4.8: Mean expected AFLWD piece count breakdown by stream class (n ac^{-1}) for trees having a DBH of at least 4 inches.

class A, the trajectories for the scenarios Alt 03, No Action, FFR Option 2 $<$ 10 ft, and FFR Option 2 $>$ 10 ft are all quite similar and produced nearly equivalent final mean LWD piece counts. The No Action and FFR scenarios have essentially identical trajectories for AFLWD in size class A, which was expected, since the large LWD logs must come from trees that are close to a stream, and these three scenarios all have a no harvest zone adjacent to a stream that is at least 80 ft wide. The Alt 49 scenario produced the smallest number of AFLWD pieces for functional LWD size class A, consistent with its having the largest harvestable area, but it still produced approximately 50% of the pieces produced by the four similar scenarios. The Alt 03 No Under Plant scenario produced the largest number of AFLWD pieces for functional size class A, producing approximately twice as many functional LWD pieces, indicating that the underplanting inhibited the development of very large trees. The variability of the functional piece count estimates for size class A were high, with standard deviations that were approximately 22% to 50% of their mean values.

The increments in the number of ALWD pieces qualifying as functional for stream size class B increased rapidly, and eventually became the dominant component of the total piece count for each of the selected management scenarios. The AFLWD piece counts for size class B and the No Action, FFR Option 2 $<$ 10 ft, FFR Option 2 $>$ 10 ft, were similar, reaching plateaus, by year 150 for the No Action scenario and year 100 for the FFR scenarios. The plateau values differ only in proportion to the size of the no harvest regions, with the plateau for the No Action scenario greater than that for the FFR Option 2 $>$ 10 ft scenario, which was, in turn, greater than the plateau for the FFR Option 2 $<$ 10 ft scenario. The piece count increments for functional size class B and the Alt 03 scenario eventually become greater than those of the Alt 03 No Under Plant scenario as the underplanted trees become large enough to contribute to LWD. The impact of the final thinning event at 70 years is readily apparent, having caused a reduction in the number of potentially available pieces in this size class for both of these scenarios. The Alt 03 scenario begins to recover its piece count in this size class near the end of the 140 year management horizon. The Alt 49 scenario produced AFLWD piece count increments that were comparable the those of the Alt 03 scenario for functional size class B. The harvest events at 50, 100, and 150 years are clearly seen to reduce the number of functional LWD pieces for this size class, after which the number of pieces rebounds slightly just prior to the next harvest event.

The AFLWD piece count increments for stream size class C increased very rapidly, and were the dominant early component of the total potentially available LWD. The AFLWD piece counts for size class C and the No Action, FFR Option 2 $<$ 10 ft, FFR Option 2 $>$ 10 ft, were, again, similar, increasing rapidly to obtain maximum values between 40 and 60 years and then beginning a slow decline. The rates of decline are directly related to the sizes of the no harvest regions for each of these scenarios, with the piece counts for the No Action scenario declining the slowest and the piece counts for the FFR Option 2 $<$ 10 ft scenario declining the fastest. The piece count increments for size class C and these three scenarios became smaller over time due to trees becoming larger, and hence producing potential functional LWD logs qualifying for size class B, and stand mortality which removed trees from the pool of available trees. Impacts from the harvest events are not particularly evident for these three scenarios and this size class, but there may be a small additional decline in LWD logs for this size class after the harvest at 150 years.

The total AFLWD piece counts, as well as the piece count increments, for size class C all declined following the harvest events for the Alt 03, Alt 03 No Under Plant, and Alt 49 management scenarios. There was an additional decline in the incremental number of functional LWD logs in this size class after the final thinning at 70 years in the Alt 03 and Alt 03 No Under Plant scenarios. After the thinning, the incremental number of functional LWD logs qualifing for size class C and the Alt 03 No Under Plant scenario continued to decline throughout the remainder of the 140 year managment horizon, while the incremental number of functional logs in this size class began to increase at approximately 110 years for the Alt 03 management scenario due to the underplanting. The total number of functional LWD pieces for size class C may have peaked just prior to the final harvest event at 150 years for the Alt 03 managment scenario, after which there was a slight decline in the incremental amount of functional LWD in size class C as the underplanted trees became large enough to qualify for size class B. The altfournine management scenario shows declines in the total and incremental number of functional LWD logs for size class C, followed by increases in the numbers of functional logs beginning 25 years post harvest, as the planted trees became large enough to fall and reach the stream. This 50 year cycle will continue, with a slow decline in the total number of functional pieces as mortality removes trees from the no harvest region in this scenario since it does not include regeneration in the no harves zone.

Finally, there were some small LWD pieces produced by each management scenario, the incremental number of pieces qualifying for stream class D. The number of small LWD pieces was typically low, and declined rapidly as trees grew and became large enough to produce logs in the larger size classes C through A. Small LWD logs were available throughout the 140 year time interval for the No Action scenario, in steadily declining amounts, as trees further from a stream achieved a size that was large enough for them to fall and reach the stream. The FFR Option 2 $<$ 10 ft and FFR Option 2 $>$ 10 ft scenarios also had declining numbers of small LWD over time, but small logs were essentially eliminated immediately following the harvest events, with slight increases as the leave trees became large enough to fall and intersect with a stream, at 110 years and 120 years, respectively, after which the numbers of small LWD logs declined. Small LWD logs were present only until the first harvest event at 50 years for the Alt 03 No Under Plant management scenario, when the trees that could produce them were all harvested. The Alt 03 management scenario had all of its small LWD logs removed at the first harvest, but began producing small LWD logs 25 years after the underplanting at 70 years, and continued to have trees that could produce small LWD logs until the end of the 140 year time horizon. The trees that could produce small LWD logs in the Alt 49 scenario were removed at every harvest event, but 25 years post harvest trees became large enough to begin producing small LWD logs again, a cycle that would repeat every 50 years.

Chapter 5

Discussion

The managed riparian buffer simulation model was designed to allow the investigation of the variability in estimates of the characteristics of managed riparian forests and to to help overcome some of the limitations of using distance independent forest stand simulators or growth and yield models (Donnelly, 1997, Hann et al., 1997) when developing strategies for managed riparian buffers having multiple treatment zones parallel to a stream. The simulation model was used to produce mean trajectories for TPA, QMD, average tree height, and BA that were consistent with expectations, as well as providing estimates of their variability, as standard deviations, estimated for each simulation year. The harvest and planting or regeneration events were clearly visible in the trajectories produced by the simulation model, indicating that the essential characteristics of the thinning and harvest treatments applied in the management zones were captured by the simulation model.

An LWD availability model (Gehringer, 2004) was also combined with the managed riparian buffer simulation model to provide estimates of the potentially available functional LWD that could be recruited into a stream. The combined simulation and LWD availability models were used to estimate mean trajectories for potentially available LWD volume and piece counts for six stream size classes. The results indicated that this combination was an effective means for identifying relative differences in potential LWD production among the management scenarios for a particular stream size class, and for identifying relative differences in potential LWD production among the different stream size classes for a particular management scenario. This approach also provides a direct measure of stream benefit, potentially available LWD, total or functional, can now be linked to management strategies and used as one of several criteria for assessing the suitabilty or sustanability of particular riparian management strategies.

Several modeling and interpretation issues relating to the creation of desirable riparian stand structures and the potential for production of LWD from managed forests having multiple treatment zones within a riparian buffer are briefly discussed in Section 5.1. An example of one possible application of a multiple zone riparian management strategy across a 10 acre riparian area is then presented in Section 5.2. Finally, some of the limitations of the managed riparian buffer simulation approach and this particular applicatioin, are outlined in Section 5.3, and several possible improvements or enhancements are mentioned in Section 5.4.

5.1 Stand structure and LWD development

Stand structure characteristics such as TPA, QMD, average tree height, and BA must be interpreted with care for managed riparian forests, as the commonly employed assumption of uniformly distributed trees within a managed buffer area may not apply. For example, larger trees may be left preferentially near a stream to provide greater protection or benefit to the stream in order to compensate for trees that may be removed in a harvest or thinning further from a stream.

Stand structure characteristics TPA, QMD, average tree height, and BA were computed using the trees having DBH values of at least 4 inches within a one acre riparian buffer. These characteristics did not represent a uniform forested area across the entire one acre managed riparian buffer, but varied by management zone and location relative to a stream. By not taking the locations of the trees relative to the stream into account for these computations the actual degree of protection or benefit provided to a stream for a particular value of any stand characteristic is difficult to assess. Additional information, for example descriptions of the management zones, the locations and sizes of the individual trees relative to a stream, or a direct measure of a forest characteristic known to provide benefit to a stream, such as the potential availability of LWD volume or pieces is necessary to properly assess potential benefit to a stream. The inclusion of such a characteristic would be of particular importance when making comparisons between natural, unmanaged riparian stands, where the uniform distribution assumption may be more reasonable, and managed riparian stands, having multiple management zones, to determine the effectiveness of particular riparian management strategies relative to some set of desired riparian forest conditions or management objectives.

An additional complication in the interpretation of the simple stand characteristics for multiple zone managed stands is the typical use of age, or time since planting, as a point of reference for the attainment of desirable structural characteristics in forest management. Once management has created complex forest structures how should age be determined? Time since planting is clearly inadequate. For example, how old is a stand having several distinct canopy layers produced from multiple harvest, planting and thinning events over a long period of time? While an average age may be computed in a number of ways, no single age could adequately describe the structure of such a stand. A distribution of ages could be substituted for a single age, but it would still fail to acknowledge the direct importance of forest structure. Further, a particular desirable forest structure may have a variety of age distributions that were capable of producing it, indicating different historical development paths, no one of which may be considered representative of the structure.

Simple age-based measures of forest structure may, therefore, not provide an adequate level of detail when applied to multiple zone managed riparian forests. Riparian forest structure is dependent on the simultaneous or joint distribution of characteristics from the individual trees, for example, the size and species of the trees and their locations relative to a stream, the historical development of the stands, and the distribution of stands across a riparian landscape. If the development of desirable structural characteristics are an objective of riparian forest management, then the forest structures of interest must be emphasized, as they are truly what are desired, rather than an age at which they may, or may not, occur.

The presence or absence of an understory can have a significant impact on forest structure and stand development. In particular, the presence of an understory may have a significant impact on the development of trees that are big enough to function in large streams. This may be seen by comparing the potentially available functional LWD results for theAlt 03 and Alt 03 No Under Plant management scenarios and stream size class A, the largest stream size considered. The Alt 03 and Alt 03 No Under Plant management scenarios were identical for times since planting less than 70 years, producing 37.8 $\mathrm{ft}^3\mathrm{ac}^{-1}$ of AFLWD volume and 0.23 AFLWD pieces ac^{-1} of potentially available functional LWD for size class A. By 100 years after planting, 30 years after the establishment of an understory, the Alt 03 management scenario had produced 391.2 $\mathrm{ft}^3\mathrm{ac}^{-1}$ of AFLWD volume and and 1.5 AFLWD pieces ac^{-1}, and the Alt 03 No Under Plant scenario had produced

425.0 $\mathrm{ft}^3\mathrm{ac}^{-1}$ of AFLWD volume and 1.6 AFLWD pieces ac^{-1}. By 140 years after planting, the Alt 03 management scenario had produced 1025.8 $\mathrm{ft}^3\mathrm{ac}^{-1}$ of AFLWD volume and 2.7 AFLWD pieces ac^{-1}, versus 1254.3 $\mathrm{ft}^3\mathrm{ac}^{-1}$ of AFLWD volume and 3.4 AFLWD pieces ac^{-1} for the Alt 03 No Under Plant management scenario, giving reductions of 18.2% in AFLWD volume and 19.2% in AFLWD pieces relative to the Alt 03 No Under Plant scenario. By 160 years after planting, the declines in potentially available functional LWD relative to the Alt 03 No Under Plant scenario had increased to 36.0% and 36.4% for potentially available LWD volume and pieces, respectively.

The lower potentially available functional LWD volumes for the Alt 03 scenario, relative to the Alt 03 No Under Plant management scenario, persisted for all of the smaller stream size classes as well, but with smaller differences as stream sizes decreased, until the trajectories of the of the two scenarios become essentially identical for total ALWD. The situation, however, reverses for potentially available functional LWD piece counts, with the Alt 03 management scenario producing 17.1% more pieces per acre by 160 years after planting than the Alt 03 No Under Plant management scenario for stream size class B, and 95.6%, 96.4%, 96.5%, on average, for stream size classes C, D, and E/F, respectively. A partial explanation for this effect is that as the minimum size of a functional LWD log becomes smaller, tree size becomes less critical in terms of LWD production, and the trees in the understory contribute functional LWD. This is consistent with the underplanting increasing competition and reducing growth in the overstory, while rapidly growing the understory, and maintaining a limiting stand volume.

The presence of an understory may, then, delay the development of trees large enough to be suitable as functional LWD in large streams, while supplying a greater number of functional LWD pieces for smaller streams and producing a forest canopy with multiple stories. The development of some desirable structural characteristics in a managed riparian forest, multiple canopy stories, may, therefore be at odds with the development of other desirable characteristics, such as functional LWD logs for large streams. The effects of an understory on the development of desirable forest structures and on the production of LWD for streams, and any associated trade-offs, must, then, be considered when modeling or evaluating management strategies for riparian forests.

The primary impact of harvesting on the potentially available LWD in the selected scenarios was to reduce the volume and number small and intermediate sized pieces, generally not affecting the volumes produced by the larger pieces. This occurs because the small and intermediate sized pieces typically come from smaller trees and trees located further from the stream, and these are the trees removed by thinning and harvest events in the scenarios. The larger LWD logs typically come from closer to a stream, and would be within the no harvest or minimal management regions adjacent to the streams.

5.2 Management scenario application on a riparian landscape

The managed riparian buffer simulation model represented a single acre in a riparian landscape. A management scenario would not be expected to be applied in a synchronized manner across a riparian landscape, but in a distributed manner where adjacent areas were at different stages of development. This could be accomplished by staggering the application of the management scenario in time to provide a diverse a set of forest structures within a riparian landscape. To demonstrate this idea, the Alt 03 management scenario was applied to a 10 acre simulated riparian landscape, where 5 adjacent acres were located along either side of a 33.1 ft stream with its center located at zero on the “Distance to stream” axis. Each acre of the riparian landscape was assumed be directly adjacent to the stream, with a width of 170 ft. The first six simulation years, $y_l = 0, 5, 10, 15, 20$ and 25 were used to define the possible initial conditions for the simulated riparian landscape. Five of the six available initial conditions were randomly selected for the one acre buffer areas on each side of the stream and assigned to them. Each acre on the 10 acre riparian landscape was then projected forward in time 50 and 100 years. Tree locations along a stream were randomly, uniformly, assigned to the individual trees within each riparian acre for the visualization.

The initial riparian landscape is shown in Figure 5.1, with a 50 year projection in Figure 5.2 and a 100 year projection in Figure 5.3. The initial riparian landscape shows some height differentiation among the acres comprising the riparian landscape, but no treatments other than the initial thinning treatment 20 years after planting have been performed. The 50 year projection shows a diverse set of forest conditions, with a corridor of larger trees along both sides of the stream and a variety of development stages represented in the outer management zones. Two stages of development in the underplanting designed to promote an understory are also evident in Figure 5.2, with a taller understory on the right stream bank. The 100 year projection, again, shows a diverse set of forest conditions, with greater size diversity within the corridor of larger trees along both sides of the stream and a much more prominent understory. The outer management zones on both sides of the stream maintain the same degree of diversity as was present in the 50 year projection since they are based on a 50 year rotation. These riparian landscape visualizations demonstrate that management within a riparian area can be an effective tool for the creation of diverse forest structures that may enhance stream functions and habitat provided by riparian forests.

5.3 Simulation model limitations

The managed riparian buffer simulation model was designed to use tree lists produced by forest stand simulators and forest growth and yield models. The degree to which the trajectories produced by the managed buffer simulation model represent the actual development of a multiple zone, managed riparian buffer depends largely on two factors. First is the degree to which the canonical tree lists produced by a particular forest stand simulator or forest growth and yield model represent the actual development of a forest stand for each of the management options. Second is the degree to which the random selection and proportional assignment of trees to management zones within a riparian buffer for a particular management scenario produces stands representative of actual stands that would have been produced under that management scenario.

5.3.1 Forest growth model

The choice of an appropriate forest stand simulator or growth and yield model to project the create the canonical tree lists for the management options is critical. No forest growth model is perfect, however, and the degree to which any particular model represents a particular situation varies. This was the primary reason the managed riparian buffer simulation model was designed to be independent of any specific forest growth model, so that the most appropriate forest growth model could be used, depending on the particular context. The stand simulator or growth and yield model chosen should be well tested and appropriate for the region. The ORGANON growth model (Hann et al., 1997), used within LMS (McCarter et al., 1998, McCarter, 2001), is a widely used forest stand simulator developed for forests of the Pacific Northwest, and was therefore considered appropriate for this application. The variant of the ORGANON model developed for the Stand Management Cooperative (Chappell et al., 1988), ORGANON-SMC version 6.0, was used to project the managment options, and was expected to produce canonical tree lists that were reasonable for the management options that were defined. The ORGANON-SMC model within LMS was used without any *a priori* calibrations, under the assumption the the model was developed for forests of western Oregon and western Washingtion, and should therefore not need to be calibrated.

A new version of the ORGANON model, ORGANON-SMC version 8.x has recently become available. Its basal area growth projections are significantly lower than those produced by version 6.0 of the model. For

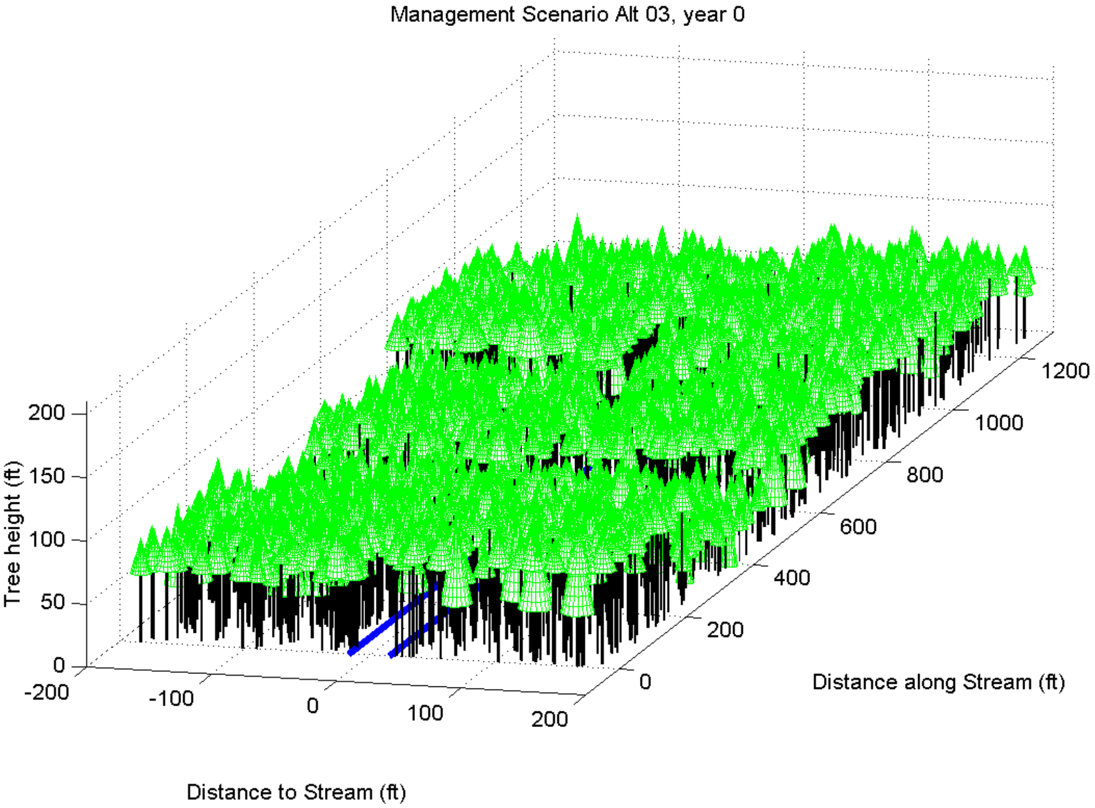

Figure 5.1: Initial 10 acre simulated landscape for the Alt 03 management scenario.

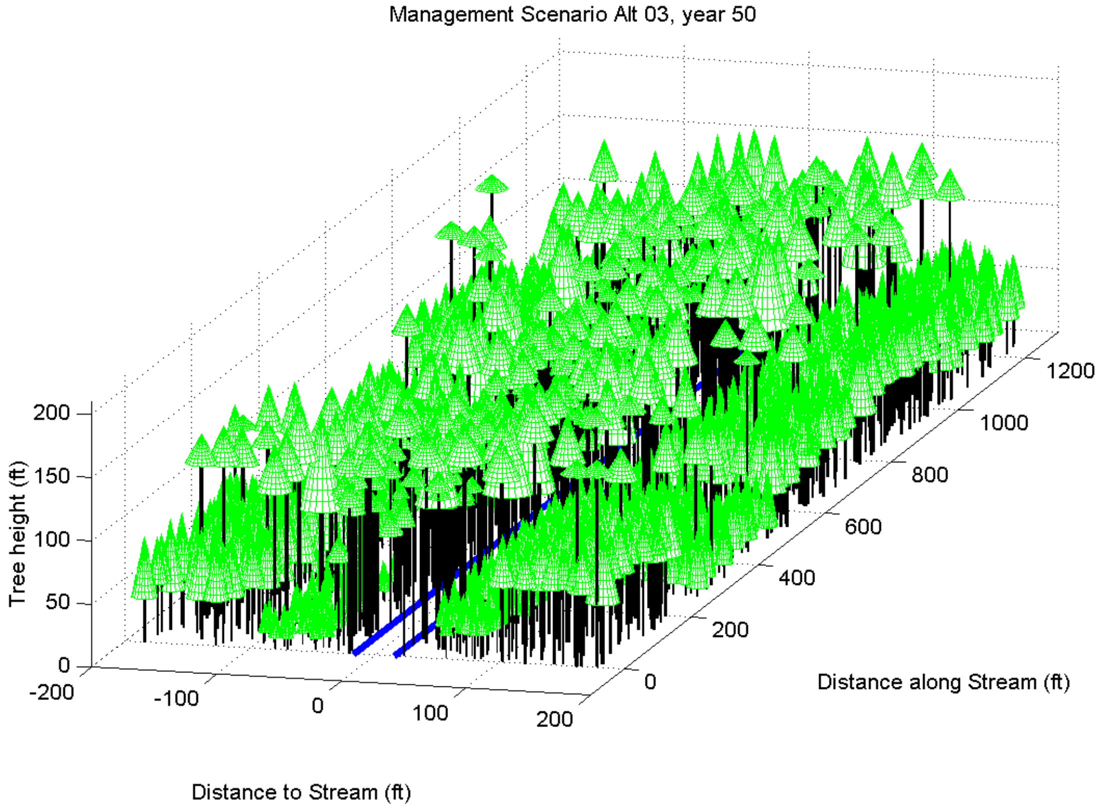

Figure 5.2: Simulated 10 acre riparian landscape for the Alt 03 management scenario at 50 years.

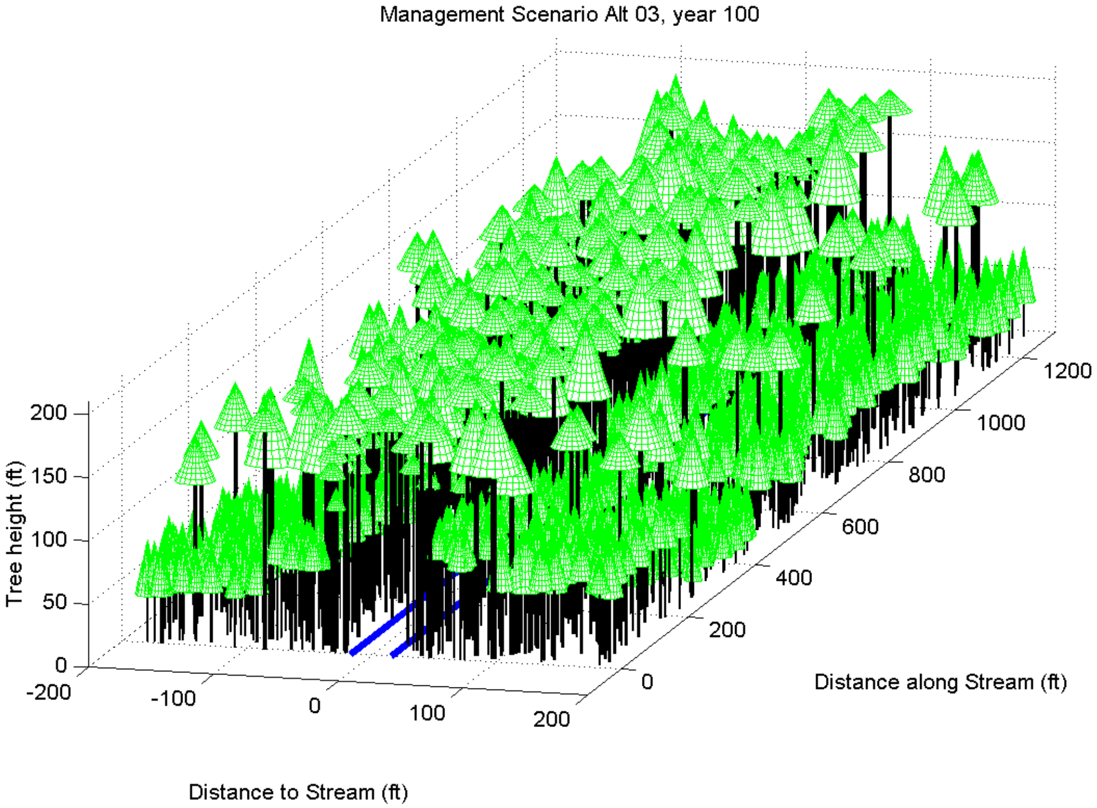

Figure 5.3: Simulated 10 acre riparian landscape for the Alt 03 management scenario at 100 years.

example, the No Action scenario projected by version 6.0 produced a final basal area value of 429.3 $\mathrm{ft}^2\mathrm{ac}^{-1}$ at 160 years while version 8.x produces a value of 357.8 $\mathrm{ft}^2\mathrm{ac}^{-1}$, a difference of 71.5 $\mathrm{ft}^2\mathrm{ac}^{-1}$. This change in basal area development brings the ORGANON model into much better agreement with Bulletin 201 (McArdle and Meyer, 1930). The change also impacts the stand trajectories, and in particular the ALWD and AFLWD values will most likely be reduced for both volume and number of pieces. The exact degree of the impacts cannot be assessed until the management option canonical tree lists are generated with the new ORAGANON-SMC model and the management scenario simulations are repeated using the new tree lists.

5.3.2 Random selection of trees and locations

The random selection and proportional representation of trees used in the managed riparian buffer simulation model were simply specific implementations of typical assumptions made when sampling forests to obtain an inventory or when modeling forest stand development. Forest stands are assumed to have uniform properties throughout their spatial extent, and trees within a stand are assumed to be interchangeable if randomly sampled. Sampled trees typically represent multiple trees within a uniform stand, and are assumed to be uniformly distributed within the stand. The tree selection and representation procedures implemented in the simulation model mimic those used when sampling actual forests, and they should, therefore, be appropriate as used and produce reasonable results.

The managed riparian buffer simulation model did not address the potential edge effects, whether from the edge of the buffer along a stream or from the edges between adjacent management zones for a management scenario. In this regard the assumptions made here were similar to those made by the majority of forest stand simulators or growth and yield models, ORGANON-SMC included. This is a difficult growth effect to capture, but it may be possible to account for it by modifying the assumption of the uniform distribution of trees within each management zone. In particular, the tree location distributions would need to be modified to place more trees near the edges where a higher local density would be expected, for example along a stream or along a management zone boundary that had shorter trees on one side than on the other. More investigation is needed to determine the feasibility of incorporating edge effects into the model using this, or some other, method.

The simulation approach was chosen specifically to address issues related to the uncertainty inherent in deriving results for a particular forest stand, using its configuration of trees, by providing estimates of the possible variability in estimates of mean values for a variety of stand characteristics. A forest stand that was representative of a particular forest structure, and the configuration of trees within that stand, was assumed to represent only one of the many possible configurations that could have occurred to produce the stand structure, as desirable stand structures may be produced by different paths of stand development, and are dependent on the specific disturbance or management histories. Repeated simulation trials, based on the assumption of a uniform distribution as the underlying distribution for tree locations within the management zones, were used as a surrogate for different stand development pathways to generate possible tree configurations. This approach may produce physically unrealizable tree configurations, due to excessive clumping of large trees for example, but these configurations were expected to occur infrequently given the stand densities and sizes of the management zones that were involved in the management scenario simulations. The random tree placement could be modified to alleviate this problem if it became necessary.

5.4 Future work and enhancements

The quality of the stand projection or growth and yield model used to obtain the canonical treelist for the management option trajectories plays a critical role in determining the outcomes from the simulation model described. Several potential deficiences in one particular model, ORGANON-SMC, relative to a particular reference data set were identified. These issues will be investigated further to identify an alternative growth model or to calibrate the ORGANON-SMC model to provide stand development trajectories that are in better agreement with observational data.

With the current implementation of the managed riparian buffer model it is not possible to directly compare the management scenarios for regions smaller than the one acre riparian buffer. To better understand the effects of distance from a stream and level of management on the potential to produce instream LWD a partition of the riparian acre into strips parallel to the stream that was common to all of the management scenarios would be useful. With such a partition the structures and potential for providing stream function, shade or LWD, and their differences between zones within a buffer or among a collection of management scenarios could be better determined. This feature would allow, for example, a direct comparison of the stand structure and potential for LWD production within the first 50 ft of a stream across all management scenarios. The addition of this feature is planned for a future version of the software.

The managed riparian buffer simulation model can also be extended to include a shade submodel that could be used to estimate the potential blocking of incoming light radiation by the forests adjacent to streams. A working prototype of this capability has alread been developed and seems promising. Enhancements to support the addition of standing dead trees or snags and fallen trees are also under consideration. The determination of tree location distributions relative to a stream within the management zones in a riparian buffer is also desirable, e.g., by obtaining empirical estimates of these distributions. The possible impacts of species composition should also be considered in this regard. Edge effects, as previously mentioned, are also of interest, and their consideration may be made possible by identifying a distribution of distances from an edge that defines the locations of trees relative to the edge. The development of a five year Douglas-fir regeneration file to coincide with the five year time step of the model is also under consideration.

The development of an interactive, graphical user interface for riparian management scenario design, simulation, and projection is being considered. The availability of such an interface would greatly enhance the utility of the managed riparian buffer simulation model, allowing access to a broader audience. An additional possibility is the linking of the managed riparian buffer simulation model with a tool such as the landscape management system McCarter (2001), McCarter et al. (1998) to facilitate the interactive development and simulation of riparian management strategies. Finally there are several of computational improvements tha tcan be made to the simulation model, particularly with regard to improving the speed of the simulations and data management.

Chapter 6

Conclusions

An individual tree based simulation model for multiple zone managed riparian buffers was developed. The model allows the definition of nested management zones within a one acre area adjacent to one side of a stream, and supports the application of a different management option within each of the defined management zones. The combined management zones and their associated management options specify a riparian management scenario whose characteristics may be projected through time. The multiple zone managed buffer simulation model uses sequences of tree lists, obtained from forest simulators or growth and yield models, representing the temporal development of forest stands for a set of management options as inputs. Management scenarios were simulated by randomly selecting trees from the management option tree lists, based on the sizes of the management zones, and assigning randomly generated spatial locations to the trees within each management zones. By including spatial information for each tree via randomly generated tree locations, the simulation model expands the range of possible applications for distance-independent forest simulators and growth and yield models, the most common variety, without the difficulty of developing a true spatially explicit model for forest stand development.

The simulation model was developed to assist in the design of management strategies for riparian forests, and was linked to a LWD availability model to provide a direct connection between the forest structure adjacent to a stream and its potential influences on stream function. The managed riparian buffer simulation model permits the direct estimation of variability in stand characteristics and potential stream function, potentially available LWD, by repeating the random tree selection and location assignments to produce a number of stands having similar structural characteristics, as a surrogate for different stand development pathways. The results obtained were consistent with expectations, and further validation of the simulation model through comparisons to actual riparian stands is necessary. The simulation model does appear to captures the development of the management scenarios, at least to the extent that the underlying growth models represent actual stand development, as the assumptions are essentially identical to those of the distance-independent growth models.

The results presented here indicated that it should be possible to create managed riparian forests that provide a significant amount of the stream function relative to an unmanaged riparian area. A number of the management scenarios produce results that were indistinguishable from one another in terms of potentially available LWD volume, while the number of potentially available LWD pieces varied due to structural differences within the stands produced by the different scenarios. The relative variability in estimates of potentially available LWD volume was also larger than those for piece counts, most likely indicating that individual tree location relative to a stream may be much more important, and variable, for LWD volume than for piece counts, with trees far from a stream potentially contributing small pieces that added little volume. There may, therefore, be a quality-quantity trade-off LWD volume, or log size, and the number LWD pieces. This may be of particular importance for smaller streams, as they would have wider effective potential delivery areas for LWD due to the smaller dimensions for functional LWD logs. A better understanding of the functions different sizes of instream LWD logs provide seems necessary to better understand the potential trade-offs that may exist between LWD size and number of pieces, to allow for better informed riparian management decisions to be made, particularly for smaller streams where both large and small LWD logs are likely to provide some benefit.

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 stands, or other natural systems, whether managed or not. The models used to support forest management decisions or policy must be constantly improved or updated to meet the demands for increased detail and to provide estimates of the inherent variability. Simulation models, such as the one described here for managed riparian buffers, 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, adding an improved distribution of tree locations that includes edge effects, by simply modifying the input distributions used to represent the particular aspects 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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