Ecological Applications, 13(5), 2003, pp. 1212–1221

IMPLICATIONS OF RIPARIAN MANAGEMENT STRATEGIES ON WOOD IN STREAMS OF THE PACIFIC NORTHWEST

Mark A. Meleason,[1,3] Stanley V. Gregory,[1] and John P. Bolte[2]

[1]*Fisheries and Wildlife Department, Oregon State University, Corvallis, Oregon, 97331-3803 USA*
[2]*Bioresources Engineering Department, Oregon State University, Corvallis, Oregon, 97331-3803 USA*

Abstract. Riparian forest management plans for numerous regions throughout the world must consider long-term supply of wood to streams. The simulation model OSU STREAMWOOD was used to evaluate the potential effects of riparian management scenarios on the standing stock of wood in a hypothetical stream in the Pacific Northwest, USA. OSU STREAMWOOD simulates riparian forest growth, tree entry (including breakage), and in-channel processes (log breakage, movement, and decomposition). Results of three simulation scenarios are reported. The first scenario assessed total wood volume in the channel from Douglas-fir plantations clearcut to the stream bank using three rotation periods (60, 90, and 120 yr). Without a forested riparian management zone, accumulation of wood in the channel was minimal and did not increase through time. In the second scenario, response of total wood volume to forested riparian management zones of widths between 6 m and 75 m was evaluated. Total wood volume associated with the 6 m wide nonharvested forest for forest ages ≥240 yr was 32% of the standing stock associated with a nonharvested forest buffer one potential tree height in width. Maximum standing stock associated with the channel for nonharvested riparian forests ≥30 m required 500-yr-old forests. In the third scenario, contribution of wood from forest plantations beyond nonharvested forests of various widths was explored. Forest plantations associated with nonharvested riparian buffers with widths >10 m contributed minimal amounts of wood volume to the stream. These results suggest that forest age and width of the nonharvested buffers are more important than the rotation age of plantation forests in providing long-term supplies of wood to streams.

Key words: large wood in streams; riparian forest management; OSU STREAMWOOD; Pacific Northwest.

Introduction

Complex interactions between riparian forests and stream systems influence the biological community and physical environment found in each system (Swanson et al. 1982, Gregory et al. 1991, Malanson 1993, Naiman and Decamps 1997). Streams influence forest conditions, which include edaphic, climatic, and disturbance regimes (e.g., Fonda 1974, Palik et al. 1998). These influences create riparian forest communities that differ from upland forests in species composition and structure (Viereck 1970, Hawk and Zobel 1974). Conversely, riparian forests influence stream conditions such as flow levels (Cleaverly et al. 2000), temperature (Brown and Krygier 1970), and nutrient concentrations (Tabbacchi et al. 1998) and are a major source of sediment and organic materials (Triska et al. 1982, Gregory et al. 1991).

Numerous studies have documented the impacts of forest harvest operations on stream systems (for example, see Gregory et al. [1987], Salo and Cundy [1987], Meehan [1991], Forest Ecosystem Management Assessment Team [FEMAT; 1993] for major reviews). The degradation of stream systems and the recognition of the functional importance of riparian forests to streams has prompted timber management plans, especially in the temperate and boreal regions, to include some level of protection for riparian zones. Protection of riparian areas, at least in the form of voluntary guidelines, has been implemented in a growing number of nations that include the United States, Canada, United Kingdom, Sweden, Australia, New Zealand, and South Africa (Gregory 1997, Boothroyd and Langer 1999). Initial goals included providing adequate shade, reducing sedimentation, and reducing the amount of forest chemicals from entering the stream (Bilby and Wasserman 1989). Research over that last 30 years has determined that wood is functionally important in many streams systems in western North America (e.g., Harmon et al. 1986), Europe (e.g., Gurnell and Sweet 1998, Herig et al. 2000), Australia (e.g., Gippel et al. 1996), and New Zealand (Evans et al. 1993). Wood in streams creates habitat for aquatic organisms and is a source of long-term nutrient loading and influences channel morphology, hydrology, and sedimentation patterns (Harmon et al. 1986, Bisson et al. 1987, Maser et al. 1988, Samuelsson et al. 1994).

Manuscript received 2 January 2002; revised 10 January 2003; accepted 4 February 2003. Corresponding Editor: J. J. Elser.

[3] Present address: National Institute of Water and Atmospheric Research, P.O. Box 11115, Hamilton, New Zealand. E-mail: m.meleason@niwa.co.nz

Recognition of the functional importance of wood in streams challenges managers and scientists to consider the long-term implications of riparian forest management on wood in streams. In western North America, one goal of riparian management strategies is to maintain ecologically adequate amounts of wood in streams though time while maintaining sustainable levels of timber production (Chamberlin et al. 1991). Amounts of wood in channels are highly variable and depend on geographic region, stream geomorphology, basin position, natural disturbance regimes, management history, and site characteristic that influence the structural and successional development of riparian forests.

A common feature in riparian management regulations is a fixed riparian management zone (RMZ) width adjacent to channels where forest harvest is limited or excluded (Gregory 1997). In the Pacific Northwest, the level of protection required is dependent on stream size and the presence of selected fish species. In this report, RMZ is a nonharvested area with natural tree recruitment. Management of forests outside of the RMZ includes clearcut harvest followed by planting of high-yield tree species. Douglas-fir plantations are most common in the Pacific Northwest and are harvested at ages between 40 to 120 yr (Williamson and Twombly 1983, Chamberlin et al. 1991). Wood can be recruited to the channel from forest plantations provided trees are of sufficient height relative to the distance to the channel.

The temporal scale required to investigate long-term implications of various riparian management strategies on amounts of wood in streams prohibits assessment through short-term field studies. Computer simulation models offer a method for exploring the likely consequences over a long time period and for many alternative strategies. Several models have been used to investigate the implications of various riparian management regimes of recruitment of wood to streams (Rainville et al. 1986, Van Sickle and Gregory 1990, Beechie et al. 2000, Bragg et al. 2000). Most models of wood in riparian forests and streams focus on the potential recruitment of wood to the stream. In-channel processes such as tree entry breakage and log breakage, movement, and decomposition have not been considered separately. Several models have incorporated a depletion rate, which includes loss from both downstream transport and decomposition (Murphy and Koski 1989, Beechie et al. 2000, Bragg et al. 2000). Transport of wood from upstream sources has been assumed to equal output of the reach for a given time interval (Murphy and Koski 1989, Van Sickle and Gregory 1990) or ignored. In this paper, we explore the consequences of riparian management strategies using a simulation model that incorporates stand dynamics (birth, growth, and, mortality), wood input from the riparian forest, which includes breakage associated with the tree fall, and in-channel dynamics of the wood (breakage, stream transport, and decay).

This study assesses the long-term consequences of various riparian management strategies on stream wood volume in the absence of catastrophic events. Influence of catastrophic disturbances such as fires (Bragg 2000), major wind storms (Steinblums et al. 1984), insect infestation (Bragg 2000), or debris flows (May 1998) can substantially influence amounts of wood in streams. However, development of management prescriptions is concerned with the long-term potential of the sites, which may or may not be realized due to the unpredictability of major episodic events. In this study, three approaches for riparian forest management were explored. In the first approach, wood was recruited from forest plantations clearcut to the stream bank at various rotation periods. In the second approach, wood was recruited from RMZs (nonharvested area) of various widths. In the third approach, wood was recruited from various combinations of RMZs of various widths and forest plantations at various rotation periods.

Methods

Model description

OSU STREAMWOOD is an individual-based stochastic model that simulates riparian forest and in-channel wood dynamics. A detailed description of this model is presented in Meleason (2001). Using this model, stream systems can be simulated from a single reach to a small basin. The model is run under a Monte Carlo procedure using an annual time step and the results are reported as average conditions per reach. The current version of OSU STREAMWOOD was developed for fifth-order and smaller streams in the coniferous forests of the Pacific Northwest. Species considered include Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* Donn ex D. Don), and red alder (*Alnus rubra* Bong.). OSU STREAMWOOD consists of a forest model and a wood model. The forest model simulates riparian forest dynamics under various management regimes. Output of the forest model is the input to the wood model and is a list of trees that have died in the current year. The wood model simulates recruitment of trees into the channel and subjects individual logs to in-stream processes that include breakage, movement, and decomposition.

The forest model is a forest-gap model based largely on ZELIG (Pacific Northwest version by Dr. Steve Garman, Forest Science Laboratory, Corvallis, Oregon, USA), JABOWA (Botkin et al. 1972, Botkin 1993), and CLIMACS (Dale and Hemstrom 1984, Dale et al. 1986). The forest model adheres closely to the original design of Botkin et al. (1972) and Shugart and West (1977), and thus shares many of its limitations (Schenk 1996). Riparian forests in the model can be up to 100 m wide and are composed of a nonharvested area (RMZ) and a harvested area (forest plantation). Harvest rotation schedules (which include thinning, clearcutting, and planting regimes) can be defined for each riparian forest. The forest model includes a soil moisture term that influences species composition and species-specific growth rates. For the simulations reported here, the soil moisture term was set sufficiently dry to exclude the initial dominance of red alder.

Output of the forest model is the input to the wood model and is a list of trees that died in the current year. Trees are assumed conical in form and fall the year they die. Tree entry is a function of distance from the stream bank, effective tree height (height to 10 cm diameter), and tree fall angle. Trees that intersect the channel undergo a randomly selected number of breakage events between zero and a maximum number of breaks. The location for each break is randomly selected using a normal distribution with a user-defined mean (and standard deviation) break location. The settings used in the simulation reported here include a maximum of five breakage events for a given tree and a mean and standard deviation breakage location of 0.6 and 0.2, respectively. Since trees do not break with respect to the location of the channel bank, logs can be partly outside of the channel. Logs that are completely outside the channel or do not meet minimum size requirements (10 cm diameter and 1 m in length) are excluded from further analysis. Total log volume is the volume of all logs that are at least partly in the channel.

Following entry, all logs are subjected to the in-channel processes of breakage, movement, and decomposition. In-channel breakage consists of two functions: chance of breakage and breakage location. Chance of log breakage is a stochastic function based on the assumptions that the likelihood of a log breaking decreases with size and increases with residence time. Breakage occurs at half the natural logarithm of length. The log movement component includes functions for chance of movement and distance moved. The likelihood of a log moving is assumed to increase with greater annual flow and decrease with increased ratio of log length to bankfull width, proportion of the piece outside the channel, and number of key pieces (i.e., number of logs with lengths $>$ bankfull width) in the reach. Annual peak flow is represented as a recurrence interval between 1 and 100 yr and generated with a random number generator using a log normal distribution. The same flow regime is used in all iterations of all simulations. The chance of movement function can be adjusted to the retentive properties of a given system, and was set conservatively to represent a relatively retentive system such as a boulder and cobble-dominated streams in the Oregon Cascade Mountains. The distance a log moves is assumed to follow a negative exponential distribution where the reciprocal of the slope is the average travel distance. This was set to 120 m for all simulations reported here. Logs are decomposed using a single exponential model with species-specific decomposition rates. Decomposition rate for logs partially in the channel is a linear extrapolation between terrestrial and aquatic decay rates as a function of the proportion of the log outside the channel.

Initial conditions

The hypothetical riparian forest and stream conditions represent a third-order channel in the Oregon Cascade Mountains at ~500 m elevation. Recruitment of wood to the channel was limited to recruitment from the riparian forest and fluvial transport from upstream reaches. All simulations started with no trees in the forest and no logs in the stream. Soil moisture and other site conditions were set to favor the establishment of a productive Douglas-fir–western hemlock forest (Fig. 1). Riparian forests in the RMZ grew under unmanaged conditions. Management of the forest plantations included planting 1000 Douglas-fir seedlings per hectare the year of the clearcut and thereafter no other trees were permitted to establish on the site (Fig. 2). In simulations that included both an RMZ and plantation forest, total width of the forest was 75 m and width of the plantation forest was the difference between the total and RMZ widths.

Each reach included a riparian forest adjacent to each bank and grown independently of each other but with identical riparian management prescriptions. Trees were assumed to fall the year they died and had an equal chance of falling in any direction. The hypothetical stream system consisted of four consecutive reaches each 200 m long and 12 m wide (active channel). Results for all simulations used in the analysis were from the farthest downstream reach with the three upstream reaches served as sources of wood through fluvial transport. The standing stock of wood was reported as total wood volume, which included the entire volume of any log that intersected one of the stream banks. The standing stock was subjected to in-channel processes (log breakage, movement, and decomposition). Logs were assumed to be conical in form and at least 1 m in length and 10 cm in diameter.

The modeling scenarios

A total of 30 simulations were conducted using an incomplete matrix design of 10 nonharvested buffer widths (0, 6, 10, 15, 20, 25, 30, 35, 40, and 75 m) by four harvest rotation periods (nonharvest, 60, 90, and 120 yr) (Table 1). Each simulation is named by RMZ width (B) and the rotation age (R). For example, ''B6R60'' represents the simulation with a 6-m nonharvested buffer width and a forest plantation cut every 60 yr. The rotation period for simulations with riparian buffers only (a nonharvested portion without a forest plantation) is designated as R0. For example, ''B6R0'' represents the simulation with a 6-m buffer without a plantation forest. Since recruitment from the riparian

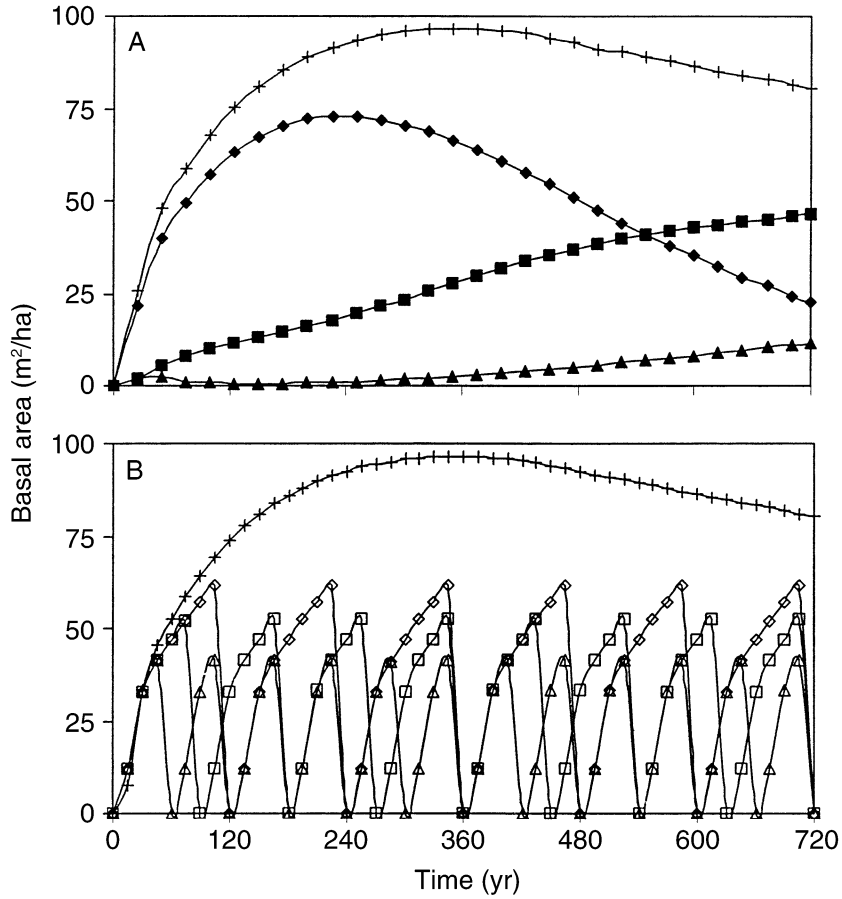

FIG. 1. Composition of the hypothetical forests used in all simulations with (A) the old-growth forest used in simulations that included an RMZ and (B) the three hypothetical plantation forests used in simulations that include plantation forests. Symbols in (A) represent basal area per hectare for Douglas-fir (filled diamonds), western hemlock (filled squares), western red cedar (filled triangles), and total forest (cross). Symbols in (B) represent basal area per hectare for plantation forest with rotation ages of 60 yr (open triangles), 90 yr (open squares), and 120 yr (open diamonds), and total basal area per hectare from the old-growth forest (crosses).

forest did not include upslope input processes, a buffer width equal to one maximum tree height is the maximum buffer width where a tree could fall and enter the stream. A buffer width of 75-m, approximately one maximum tree height, was assumed wide enough to include all input events from the riparian forest and referred to as the standard run because it represented the maximum potential recruitment to the stream from the riparian forest.

All simulations were for 720 yr and 250 iterations. The simulations were divided into three series. In the first series, recruitment of wood to the channel was limited to plantation forests clearcut to the stream bank at 60-, 90-, and 120-yr rotation cycles (Table 1, row 1). In this first series, no wood was assumed to enter the stream as a result of the harvest operation. The second series of simulations (Table 1, nonharvested column) varied the RMZ width from 6 m to 40 m and did not include any wood contributed from beyond the buffer. The third series of simulations included recruitment from both the RMZ and forest plantation using all combinations of three rotation periods and six RMZ widths (Table 1, indicated by box).

RESULTS AND DISCUSSION

Total wood volume from the standard run

The forest in the standard run simulation consisted of a 75-m wide RMZ with a maximum basal area of 96 m^2/ha (Fig. 1A). Total wood volume for a given time in the standard run simulation represented the maximum wood standing stock at any time for the hypothetical stream. A little over 50 yr was required to exceed 5 m^3/100 m of stream length (Fig. 2A–C and Fig. 3A). Maximum total wood volume accumulated was 176 m^3/100 m of stream length at year 525 and then declined to 150 m^3/100 m of stream length by year 720 (Fig. 3A). The decline in total volume after 525

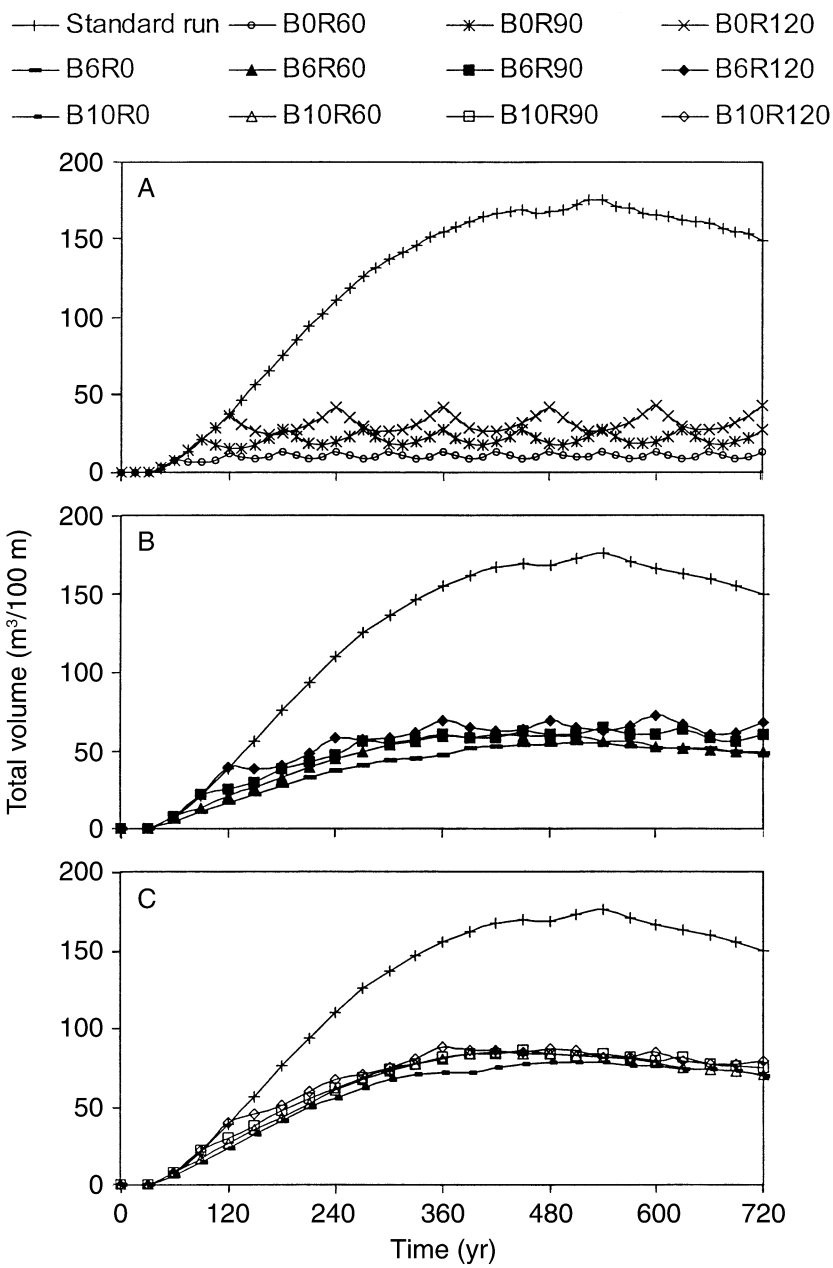

FIG. 2. Total wood volume from RMZ forest widths of (A) 0-m, (B) 6-m, and (C) 10-m with the plantation forests clearcut at 60-yr (○), 90-yr (□), and 120-yr (◇) intervals. The contribution from the plantation beyond the 6-m and 10-m RMZ is the difference in total wood volume from RMZ forests with plantation forests and RMZ forests without plantation forests (▬). Total wood volume from the 75-m RMZ (+), which represents a buffer width of one tree height, defines the maximum potential total wood volume for the site. Total wood volume includes the volume of all logs intersecting at least one stream bank.

years resulted from changes in species composition of the forest (Fig. 1A). Initially, the forest was dominated by Douglas-fir, a shade-intolerant species, but was eventually replaced by western hemlock, a shade-tolerant species. Since maximum height of Douglas-fir exceeds western hemlock by 15 m (Franklin and Waring 1980), eventual dominance of western hemlock decreases total volume of wood in the channel.

Total wood volume from forest plantations

In the first series of simulations (Table 1), riparian management consisted of Douglas-fir plantations cut to the stream bank using three rotation periods. The forest for these simulations achieved maximum basal areas of 45, 55, and 65 m^2/ha on the year of the harvest for the 60-, 90-, and 120-yr rotation cycles (Fig. 1B). Total

TABLE 1. Design of simulations.

Buffer width (m)	Nonharvested	Harvest rotation (yr) 60	90	120
0	NA	B0H60	B0H90	B0H120
6	B6R0	**B6R60**	**B6R90**	**B6R120**
10	B10R0	**B10R60**	**B10R90**	**B10R120**
15	B15R0	**B15R60**	**B15R90**	**B15R120**
20	B20R0	**B20R60**	**B20R90**	**B20R120**
25	B25R0	**B25R60**	**B25R90**	**B25R120**
30	B30R0	**B30R60**	**B30R90**	**B30R120**
35	B35R0	NA	NA	NA
40	B40R0	NA	NA	NA
75	standard run	NA	NA	NA

Notes: A total of 30 simulations were conducted using an incomplete matrix design of 10 RMZ widths (nonharvested forests) by four harvest rotation periods. The simulations were divided into three series. In the first series, plantation forests were clearcut to the stream bank at three different rotation periods (row 1). In the second series, recruitment was limited to the nonharvested buffer (nonharvested column). The third series of simulation included recruitment from various combinations of RMZ widths and forest plantation rotation periods (indicated by boldface type). NA represents simulations that were not included in the analysis and standard run is the simulation of a forest with RMZ width of 75 m, which represents the maximum recruitment to the stream.

wood volume from the three simulations without RMZs was similar to the standard run up to the first harvest cycle (Fig. 2A). The standing stock at the year of the second rotation harvest for the 60-, 90-, and 120-yr plantations was 31%, 36%, and 38% of the standing stock of the standard run. From the third rotation cycle to the end of the simulation, the proportion of the standing stock of the standard run ranged from 5% to 17% for the 60-yr, 11% to 22% for the 90-yr, and 15% to 29% for the 120-yr plantation forest.

After each harvest event, total volume of wood decreased indicating that depletion from in-channel processes exceeded recruitment. The time required after harvest for recruitment rate to equal depletion rate was approximately half the rotation period allowing accumulation of standing stock of wood only in the last half of rotation. As a result, this management approach provided only a fraction of the potential volume for a site (Fig. 2A).

Total wood volume as a function of RMZ width

In the second series of simulations (Table 1), recruitment to the channel was limited to the RMZ width of the riparian forest. All forests were identical to the standard run in terms of density, species composition, and basal area (Fig. 1A). Wood recruitment to the channel was limited to the simulated RMZ, which ranged from 6 m to 40 m in width. Buffer width and stand age strongly influenced total wood volume associated with the stream (Fig. 3A and B).

In general, the greater the RMZ width, the greater standing stock of wood associated with the stream (Fig. 3A). However, relative to the standing stock of the standard run, total wood volume was generally >90% of the standard run for all buffer widths ≥30 m (Fig. 3B) for a given stand age, indicating that the majority of total volume is contributed within the first 30-m from the stream. This result is consistent with field observations reported in McDade et al. (1990), who examined source distance (slope distance from the stream bank to the base of the source tree) in 39 streams adjacent to either mature conifer (80–200-yr-old) or old-growth conifer (>200-yr-old) riparian forests in western Oregon and Washington. Approximately 90% of the logs originated within 26 m of the channel in mature conifer and 36 m of the channel in the old-growth stands (McDade et al. 1990). Total volume of wood through time was reported for all simulations, which is a more conservative measure of wood abundance than the number of pieces. The contribution of total volume from 50 m to 75 m was <5% of the standing stock for the standard run at year 525 (the year with the maximum standing stock).

The standing stock associated with RMZ widths <30 m were limited by buffer width beyond a given forest age. For example, the forest age required for the standing stock of a given RMZ width to be <90% of the standing stock of the standard run was 43 yr for the 10-m RMZ, 90 yr for the 20-m RMZ, and 178 yr for the 25-m RMZ. For each RMZ width, potential recruitment was fully realized at a specific stand age, as indicated by an asymptotic standing stock (Fig. 3A). For example, the 6-m RMZ width achieved its maximum potential relative to the standard run by 200 yr, and thereafter was ~32% of the potential total wood volume for the hypothetical stream (Fig. 3B). The 10-m RMZ width was <50% of the standing stock of the standard run by year 280, and the maximum potential for the 15-m, 20-m, and 25-m RMZ relative to the standing stock of the standard run was 63%, 73%, and 82% respectively (Fig. 3B).

In sum, these simulations indicate that the standing stock of wood associated with the stream was influenced by the age of the forest and the width of the buffer. For buffer widths <30 m, a forest age was obtained whereby the standing stock was limited by the width of the buffer.

Contribution of wood beyond the RMZ

The third series of simulations (Table 1) evaluated the contribution of wood from forest plantations grown beyond native riparian forests. All combinations of three rotation ages (60, 90, and 120 yr) by six RMZ widths (6, 10, 15, 20, 25, and 30 m) were simulated (Table 1). Total wood volume contributed from the forest plantation was quantified as the difference between the simulation that included recruitment from both the nonharvested and plantation forest and the simulation that recruited wood from the nonharvested area only (Fig. 2B and C).

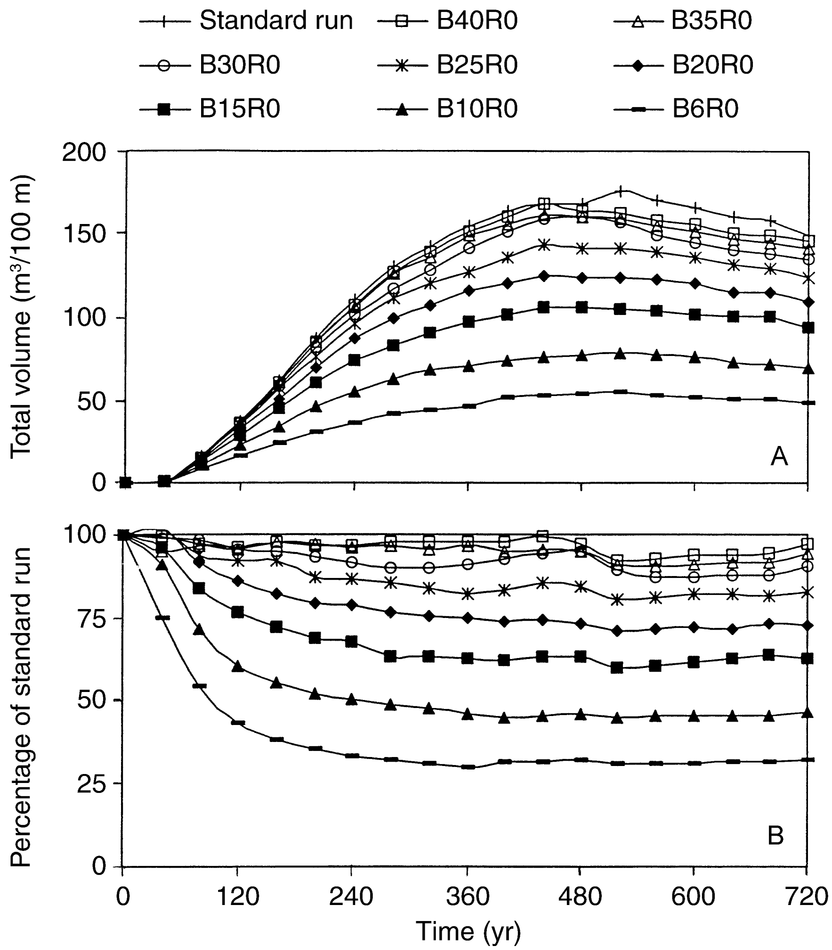

FIG. 3. Total wood volume associated with the channel by RMZ widths expressed (A) as m^3/100 m of stream length and (B) as a percentage of the standing stock from the nonharvested, 75-m forest simulation. Wood recruitment from plantations forests was excluded in these simulations.

The greatest contribution of wood from the forest plantation was with a 6-m buffer (Fig. 2B). Without the contribution of the plantation forests (B6R0 in Table 1), the standing stock at years 60, 90, and 120 was 63%, 52%, and 43% of the standing stock of the standard run (Fig. 2B). By including recruitment from the plantation forests, the standing stock at the end of the first rotation for each of the three plantation forests was equal to or slightly greater than the standing stock of the standard run, and then declined sharply. The contribution from the forest plantation at the end of the remaining 60-yr rotations ranged from <1% to 12% of the standing stock of the standard run. The contribution of standing stock at the end of the remaining rotations for the 90- and 120-yr plantation forest ranged from 6% to 14% for the 90-yr rotation and 9% to 20% for the 120-yr rotation.

Contribution to standing stock from the plantation forest beyond a 10-m RMZ was less than from the plantation forest beyond 6 m (Fig. 2C). Without the contribution of the plantation forests (B10R0 in Table 1), the standing stock at years 60, 90, and 120 was 78%, 70%, and 61% of the standing stock of the standard run (Fig. 2C). By including recruitment from the plantation forests, the standing stock at the end of the first rotation for each of the three plantation forests was equal to or slightly greater than the standing stock of the standard run, and then declined. The contribution at the end of the remaining 60-yr rotations ranged from <1% to 8% of the standing stock of the standard run. The contribution of standing stock at the end of the remaining rotations for the 90 and 120-yr plantation forest ranged from 3% to 9% for the 90-yr rotation and 5% to 10% for the 120-yr rotation.

The contribution to the standing stock from the plantation forest associated with RMZ widths >10 m was minimal. The 15-m RMZ without the contribution of the plantation forests (B15R0 in Table 1) accounted for 88%, 86%, and 77% of the standing stock of the standard run at years 60, 90, and 120. By the end of the second rotation, the contribution from the plantation forest beyond a 15-m RMZ was <2% for the 60-yr and

$<$5% for the 90-yr and 120-yr rotation forests. By the end of the second rotation for the 20-m RMZ, the contribution from the plantation forest was $<$3% for all three plantation forest simulations.

These results suggest that, for rotation ages up to 120 yr, plantation forests have very little influence on standing stock associated with the channel if the nonharvested buffers are at least 10 m wide.

Influence on model assumptions on simulated results

The goal of these simulations was to assess the long-term consequences of various riparian management strategies on standing stock of wood in streams. All nonharvested forests were identical in structure and species composition (Fig. 1A) and differed only by RMZ width. Likewise, all forest plantations were identical even-aged stands of Douglas-fir and differed only by rotation age (Fig. 1B). Plantation forests were not thinned because a variety of thinning prescriptions could be applied to each of the three rotation ages, which would result in a variety of recruitment rates from the plantation forests (Beechie et al. 2000).

Total wood volume (in-channel volume and volume outside the channel) as opposed to in-channel volume was used as the primary comparison measure because it is less sensitive to the flow regime. A greater proportion of the in-channel volume moves than the total wood volume for a given flow event. Total volume in the standard simulation at year 500 (171 m^3/100 m of channel length) was somewhat lower than the observed volume (264 m^3/100 m of channel length) in a section of Mack Creek adjacent to a 500-yr-old riparian forest in Cascade Mountains, Oregon. The underestimate in total volume may be due to the random tree fall regime. Preliminary analysis of the fall regime at Mack Creek suggests that tree fall may not be completely random, which would contribute substantially more wood to the channel. Total wood volume for the standard run with a fall regime that forced all trees to fall directly towards the channel had a total volume of 520 m^3/100 m at year 500, which is three times the total volume than using the random fall regime. However, in-channel wood volume is the measure commonly reported from wood studies (Harmon et al. 1986). The in-channel volume from the standard simulation at year 500 with a random fall and a directional fall regime was 601 m^3/100 m and 1602 m^2/100 m respectively. The observed in-channel volume in the study reach at Mack Creek was 800 m^3/100 m. Other in-channel wood volumes observed in streams with similar forest type and age, with the mean channel width in parentheses, include Cold Creek 850 m^3/100 m (7.0 m) and North Fork of Winberry Creek 700 m^3/100 m (8.5 m) (Harmon et al. 1986).

Structure and relative species dominance in riparian forests of the Cascade Mountain, Oregon are highly variable (Kauffman 1988, Naiman et al. 1998). The simulated riparian forest represented productive, conifer-dominated forests in the Cascade Mountains and was calibrated using simulations from ZELIG (S. Garman, *personal communication*). Maximum basal area of the simulated native forest was 96 m^2/ha between years 300 to 400, when 63% to 70% of the basal area was Douglas-fir, and 80 m^2/ha at year 720, when 60% of the basal area was western hemlock. Observed basal areas in old-growth ($>$400-yr-old) Douglas-fir/western hemlock stands in the western Oregon Cascades (H. J. Andrews Experimental Forest) ranged 70 m^2/ha to 140 m^2/ha and depended on the relative dominance of the two species. Plots with the greatest basal areas were dominated by Douglas-fir and plots dominated by western hemlock did not exceed 84 m^2/ha (Grier and Logan 1977).

These simulations also did not take into account the influence of catastrophic events such as windthrow, fire, landslides, and debris flows on standing stock of wood associated with streams. Therefore, these simulations represent long-term potentials for a given buffer width and forest age, which may or may not be realized due to the unpredictability of major episodic events. For example, narrow buffers have been found to be extremely vulnerable to windthrow within the first decade of formation (Steinblums et al. 1984). Susceptibility to windthrow depends on the exposure of the site to the most damaging winds. For these simulations, the sites were assumed to be protected from windthrow.

Conclusion

Riparian forest management goals typically include the long-term supply of wood to streams. In this report, long-term implications of selected riparian management strategies were explored with a computer simulation model. Simulation modeling provides a platform to examine standing stocks in streams over time scales associated with forest succession and development. Our results suggest that the width of the nonharvested buffer and forest age are the most important factors associated with providing a long-term supply of wood to streams. Plantation forests under typical rotation ages, even in combination with a nonharvested buffer, can provide only a fraction of the long-term potential of the site.

Although our results suggest that a 30-m buffer width would be sufficient to maintain the long-term recruitment of wood to streams for the Douglas-fir/western hemlock riparian forests, it may not be wide enough for other riparian forest functions, including those associated with the terrestrial environment. For example, a forest edge in a Douglas-fir forest in western Oregon, USA, was found to influence relative humidity up to 240 m into the forest (Chen et al. 1995). The influence of a double edge effect on the riparian forest created with the harvest of the plantation forest beyond the riparian buffer is poorly understood. Increase in mortality rates of various tree species at the edge have been observed (Young and Mitchell 1994) as well as a substantial increase in blowdown rates within the first 5 yr after harvest (Steinblums et al. 1984). The selection of a buffer width that would provide adequate protection for stream ecosystems and riparian forest functions may vary by landscape position and local site conditions (Bragg and Kershner 1999).

Acknowledgments

This research was sponsored by a National Science Foundation (NSF) Grant (DEB 9632921) supporting the Long-Term Ecological Research Program at the H. J. Andrews Experimental Forest. The authors would like to thank two anonymous reviewers for their suggestions to improve this manuscript and Mark Hutchinson, Steven Garman, and Edin Zulic for their advice on the art of computer programming.

Literature Cited

Beechie, T. J., G. Pess, P. Kennard, R. E. Bilby, and S. Bolton. 2000. Modeling recovery rates and pathways for woody debris recruitment in Northwestern Washington streams. North American Journal of Fisheries Management **20**:436–452.

Bilby, R. E., and L. J. Wasserman. 1989. Forest practices and riparian management in Washington State: data based regulation development. Practical approaches to riparian resource management: an educational workshop. Pages 87–94 *in* R. E. Gresswell, B. A. Barton, and J. L. Kershner, editors. Practical approaches to riparian resource management: an educational workshop. U.S. Bureau of Land Management, Billings, Montana, USA.

Bisson, P. A., R. E. Bilby, M. D. Bryant, C. A. Dolloff, G. B. Grette, R. A. House, M. L. Murphy, K. V. Koski, and J. R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Pages 143–190 *in* E. O. Salo and T. W. Cundy, editors. Streamside management: forestry and fishery interactions. College of Forest Resources, University of Washington, Seattle, Washington, USA.

Boothroyd, I. K. G., and E. R. Langer. 1999. Forest harvesting and riparian management guidelines: a review. Technical Report 56. National Institute of Water and Atmospheric Research, Hamilton, New Zealand.

Botkin, D. B. 1993. Forest dynamics: an ecological model. Oxford University Press, New York, New York, USA.

Botkin, D. B., J. F. Janak, and J. W. Wallis. 1972. Rationale, limitations, and assumptions of a northeastern forest growth simulator. IBM Journal of Research and Development **16**: 101–116.

Bragg, D. C. 2000. Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system. Ecology **8**:1383–1394.

Bragg, D. C., and J. L. Kershner. 1999. Coarse woody debris in riparian zones. Journal of Forestry **97**:30–35.

Bragg, D. C., J. L. Kershner, and D. W. Roberts. 2000. Modeling large woody debris recruitment for small streams of the Central Rocky Mountains. USDA Forest Service General Technical Report RMRS-55.

Brown, G. W., and J. T. Krygier. 1970. Clear-cut logging on stream temperature. Water Resources Research **6**:1133–1139.

Chamberlin, T. W., R. D. Harr, and F. H. Everest. 1991. Timber harvesting, silviculture, and watershed processes. Pages 181–206 *in* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publication 19. American Fisheries Society, Bethesda, Maryland, USA.

Chen, J., F. J. Franklin, and T. A. Spies. 1995. Growing-season microclimatic gradients from clearcut edges into old-growth Douglas-fir forests. Ecological Applications **5**: 74–86.

Cleaverly, J. R., J. R. Thibault, J. Pearce, and C. Dahm. 2000. Seasonal 3-D eddy covariance evaportranspiration estimates from a middle Rio Grande (New Mexico) riparian ecosystem. Bulletin of the North American Benthological Society **17**:134.

Dale, V. H., and M. Hemstrom. 1984. CLIMACS: a computer model of forest stand development for Western Oregon and Washington. USDA Forest Service Research Paper PNW-327.

Dale, V. H., M. Hemstrom, and J. F. Franklin. 1986. Modeling the long-term effects of disturbance on forest succession, Olympic Peninsula, Washington. Canadian Journal of Forest Research **16**:56–67.

Evans, B. F., C. R. Townsend, and T. A. Crowl. 1993. Distribution and abundance of coarse woody debris in some southern New Zealand streams from contrasting forest catchments. New Zealand Journal of Marine and Freshwater Research **27**:227–239.

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic, and social assessment. Forest Ecosystem Management Assessment Team (FEMAT) 1993-793-071. GPO, Washington, D.C., USA.

Fonda, R. W. 1974. Forest succession in relation to river terrace development in Olympic National Park, Washington. Ecology **55**:927–942.

Franklin, J. F., and R. H. Waring. 1980. Distinctive features of the Northwest coniferous forest: development, structure, and function. Pages 59–86 *in* R. H. Waring, editor. Forests: fresh perspectives from ecosystem analysis. Proceedings of the 40th annual biology colloquium. Oregon State University Press, Corvallis, Oregon, USA.

Gippel, C. J., B. L. Finlayson, and I. C. O'Neill. 1996. Distribution and hydraulic significance of large woody debris in a lowland Australian river. Hydrobiologia **318**:179–194.

Gregory, S. V. 1997. Riparian management in the 21st century. Pages 69–86 *in* K. A. Kohm and J. F. Franklin, editors. Creating a forestry for the 21st century: the science of ecosystem management. Island Press, Washington, D.C., USA.

Gregory, S. V., G. A. Lamberti, D. C. Erman, K. V. Koski, M. L. Murphy, and J. R. Sedell. 1987. Influence of forest practices on aquatic production. Pages 233–255 *in* E. O. Salo and T. W. Cundy, editors. Streamside management: forestry and fishery interactions. Institute of Forest Resources, University of Washington, Seattle, Washington, USA.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience **41**:540–551.

Grier, C. C., and R. S. Logan. 1977. Old-growth *Pseudotsuga menziesii* communities of a western Oregon watershed: biomass distribution and production budgets. Ecological Monographs **47**:373–400.

Gurnell, A. M., and R. Sweet. 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. Earth Surface Processes and Landforms **23**:1101–1121.

Harmon, M. E., et al. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research **15**:133–302.

Hawk, G. M., and D. B. Zobel. 1974. Forest succession on alluvial landforms of the McKenzie River valley, Oregon. Northwest Science **48**:245–265.

Hering, D., J. Kail, S. Eckert, M. Gerhard, E. I. Meyer, M. Mutz, and I. Weiss. 2000. Coarse woody debris quantity and distribution in Central-European streams. International Review of Hydrobiology **85**:5–23.

Kauffman, J. B. 1988. The status of riparian habitats in Pacific Northwest forests. Pages 45–55 *in* K. J. Raedeke, editor. Streamside management: riparian wildlife and forestry interactions. Contribution 59. Institute of Forest Resources, University of Washington, Seattle, Washington.

Malanson, G. P. 1993. Riparian landscapes. Cambridge University Press, New York, New York, USA.

Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin. 1988. From the forest to the sea: a story of fallen trees. USDA Forest Service General Technical Report PNW-229.

May, C. L. 1998. Debris flow characteristics associated with forest practices in the central Coast Range. Thesis. Oregon State University, Corvallis, Oregon, USA.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. Van Sickle. 1990. Source distance for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research **20**:326–330.

Meehan, W. R. 1991. Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publication 19. American Fisheries Society, Bethesda, Maryland, USA.

Meleason, M. A. 2001. A simulation model of wood dynamics in Pacific Northwest streams. Dissertation. Oregon State University, Corvallis, Oregon, USA.

Murphy, M. L., and K. V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management **9**:427–436.

Naiman, R. J., and H. Decamps. 1997. The ecology of interfaces: riparian zones. Annual Review of Ecology and Systematics **28**:621–658.

Naiman, R. J., K. L. Fetherston, S. J. McKay, and J. Chen. 1998. Riparian forests. Pages 289–323 *in* R. J. Naiman and R. E. Bilby, editors. River ecology and management: lessons from the Pacific coastal ecoregion. Springer-Verlag, New York, New York, USA.

Palik, B., S. W. Golladay, P. C. Goebel, and B. W. Taylor. 1998. Geomorphic variation in riparian tree mortality and stream coarse woody debris recruitment from record flooding in a coastal plain stream. Ecoscience **5**:551–560.

Rainville, R. C., S. C. Rainville, and E. L. Linder. 1986. Riparian silvicultural strategies for fish habitat emphasis. Pages 186–196 *in* Foresters's future: leaders or followers. Society of American Foresters National Conference Proceedings. SAF Publication 8-13, Society of American Foresters, Bethesda, Maryland, USA.

Salo, E. O., and T. W. Cundy. 1987. Streamside management: forestry and fishery interactions. College of Forest Resources, University of Washington, Seattle, Washington, USA.

Samuelsson, J., L. Gustafsson, and T. Ingelog. 1994. Dying and dead trees. A review of their importance for biodiversity. Swedish Threatened Species Unit, Uppsala, Sweden.

Schenk, H. J. 1996. Modeling the effects of temperature on growth and persistence of tree species: a critical review of tree population models. Ecological Modelling **92**:1–32.

Shugart, H. H., and D. C. West. 1977. Development of an Appalachian deciduous forest succession model and its application to assessment of the impact of the chestnut blight. Journal of Environmental Management **5**:161–179.

Steinblums, I. J., H. A. Froehlich, and J. K. Lyons. 1984. Designing stable buffer strips for stream protection. Journal of Forestry **82**:49–52.

Swanson, F. J., S. V. Gregory, J. R. Sedell, and A. G. Campbell. 1982. Land–water interactions: the riparian zone. Pages 267–291 *in* R. L. Edmonds, editor. Analysis of coniferous forest ecosystems in the Western United States. US/IBP synthesis series 14. Hutchinson Ross Publishing, Stroudsburg, Pennsylvania, USA.

Tabacchi, E., D. L. Correll, R. Hauer, G. Pinay, A. M. Planty-Tabacchi, and R. C. Wissmar. 1998. Development, maintenance, and role of riparian vegetation in the river landscape. Freshwater Biology **40**:497–516.

Triska, F. J., J. R. Sedell, and S. V. Gregory. 1982. Coniferous forest streams. Pages 292–332 *in* R. L. Edmonds, editor. Analysis of coniferous forest ecosystems in the Western United States. US/IBP synthesis series 14. Hutchinson-Ross Publishing, Stroudsburg, Pennsylvania, USA.

Van Sickle, J., and S. V. Gregory. 1990. Modeling inputs of large woody debris to streams from falling trees. Canadian Journal of Forest Research **20**:1593–1601.

Viereck, L. A. 1970. Forest succession and soil development adjacent to the Chena River in interior Alaska. Arctic and Alpine Research **2**:1–26.

Willamson, R. L., and A. D. Twombly. 1983. Pacific Douglas-fir. Pages 9–12 *in* R. M. Burns, technical compiler. Silvicultural systems for the major forest types of the United States. Agriculture Handbook No. 445. USDA Forest Service, Washington, D.C., USA.

Young, A., and N. Mitchell. 1994. Microclimate and vegetation edge effects in a fragmented podocarp–broadleaf forest in New Zealand. Biological Conservation **67**:63–72.