

Managing Plantation Forests to Provide Short- to Long-Term Supplies of Wood to Streams: A Simulation Study Using New Zealand's Pine Plantations

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ABSTRACT / Riparian functions such as the recruitment of wood to streams take decades to recover after a clear-fell harvest to the stream edge. The implications of two sets of riparian management scenarios on the short- and long-term recruitment of wood to a hypothetical stream (central North Island, New Zealand) were compared through simulation modeling. In the first set (native forest buffer), a designated treeless riparian buffer was colonized by native forest spe-

cies after a pine crop (*Pinus radiata*) had been harvested to the stream bank. In the second set (pine to native forest buffer), native forest species were allowed to establish under the pine canopy in a designated riparian buffer. In general, the volume of wood was greater in streams with wider buffers (5-m to 50-m) and this effect increased with forest age (800 years). The pine to native forest buffer supplied more wood to the stream more quickly, and matched the long-term supply to the stream from the native forest buffer. For the native forest buffer, total wood volume was minimal for the first 70 years and then increased uniformly for the remainder of the simulation. In contrast, the pine to native forest buffer produced a bimodal response in total wood volume with the initial sharp peak at year 100 attributed to pine recruitment and a second more gradual peak lasting for the rest of the simulation, which was similar to levels in the native forest simulations. These results suggest that existing plantations could be an important source of wood to the stream during the first 100+ years of native forest development.

A riparian forest is an area of tree-dominated vegetation adjacent to an aquatic environment. Conceptually, the riparian forest can be delineated as a three-dimensional zone encompassing all processes and functions influenced by the direct interaction between aquatic and terrestrial environments (based on Gregory and others 1991). Much research has been conducted over the last two decades on the influences of riparian forests on the biotic community, and physical and chemical processes in aquatic systems (e.g., Triska and others 1982, Gregory and others 1991, Malanson 1993, Naiman and others 1998, Tabacchi and others 1998). Research conducted in New Zealand, for example, has found that riparian forests affect air temperature (Meleason and Quinn 2004), stream

temperature (Rutherford and others 1997), water quality (Parkyn and others 2003), sediment loads (Mosley 1981), channel stability (Parkyn and others 2003), habitat for adult aquatic insects (Collier and Smith 1998), and fish (Rowe and Smith 2003), and recruitment of organic material including leaves, twigs, and large wood (Quinn and others 1997, Evans and others 1993b).

Management of timber-producing lands may severely degrade stream ecosystems if provisions to protect the stream environment are not adopted (Graynoth 1979, Chamberlin and others 1991, Bisson and others 1992). The inclusion of a riparian buffer is a common management approach used to reduce forest harvest impacts on streams (Clinnick 1985, Castelle and others 1994, Fischer and others 2000). The impact of removing all trees from the riparian zone can last from years to centuries, depending on riparian function (Gregory and others 1987). In particular, the important function of supplying wood to the stream will take a relatively long time to recover (Bisson and others 1987).

KEY WORDS: Wood in streams; Riparian forest management; *Pinus radiata*; LINKNZ; OSU STREAMWOOD; New Zealand

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Numerous studies have characterized the amount (by volume, density, or biomass) and role of wood in streams (Triska and Cromack 1980, Harmon and others 1986, Bilby and Bisson 1998, Gregory and others 2003). Functionally, wood influences channel morphology, hydrology, and sedimentation patterns, which in turn influences nutrient dynamics and habitat for aquatic organisms (Bisson and others 1987, Maser and others 1988, Gurnell and others 2002). Initially, most research on wood in streams was conducted in the Pacific Northwest of North America (Lammel 1972, Harmon and others 1986), but more recent studies have been conducted elsewhere in North America and in many temperate regions (e.g., Wallace and Benke 1984, Gippel and others 1996, Piegay and Gurnell 1997, Hering and others 2000).

In New Zealand, a small but growing body of research has been conducted on the abundance and role of wood in streams. In general, this research suggests that wood is relatively abundant and functionally important. In-channel wood volumes measured in pristine native forest streams 3 to 6 m in width range widely, from $6 \text{ m}^3 \text{ ha}^{-1}$ to $469 \text{ m}^3 \text{ ha}^{-1}$ (Mosley 1981, Evans and others 1993a, Quinn and others 1997, Baillie and Davies 2002, Meleason and others, in preparation), and are comparable to volumes found in northern Colorado streams ($93 \text{ m}^3 \text{ ha}^{-1}$ to $254 \text{ m}^3 \text{ ha}^{-1}$ in Richmond and Fausch 1995) and Great Smoky Mountain streams in Tennessee ($70 \text{ m}^3 \text{ ha}^{-1}$ to $300 \text{ m}^3 \text{ ha}^{-1}$ in Harmon and others 1986). In-channel volume measured in streams flowing through pine plantations shows similar variation, ranging from $0 \text{ m}^3 \text{ ha}^{-1}$ to $327 \text{ m}^3 \text{ ha}^{-1}$ (Evans and others 1993a, Quinn and others 1997, Baillie and others 1999, Ballie and Davies 2002). Wood in both pine and native streams has been found to influence channel morphology and pool formation (Mosley 1981, Quinn and others 1997, Baillie and Davies 2002, Meleason and others, in preparation) and provide habitat for aquatic invertebrates (Tank and Winterbourn 1996, Collier and Halliday 2000, Collier and Smith 2003) and fish (Rowe and Smith 2003).

Forest harvest operations in New Zealand are largely confined to tree plantations, which occupy 6% of the total land area (20% of the total forest area) (NZFOA 2001), although privately owned indigenous forests (2% of the land area) are also subjected to timber production (Taylor and Smith 1997). The vast majority (90%) of the plantations are composed of *Pinus radiata*, and one third of these are located in the central North Island (NZFOA 2001). Harvest plans must be approved by the local regional council and are based on guidelines developed by the timber industry (Visser and Smith 1993) and government agencies

(Collier and others 1995a, 1995b). Typical management practices include clear-cutting the 25- to 30-year-old plantations to the stream edge followed by the removal of all harvest slash from the stream (Boothroyd and Langer 1999). Retention of riparian buffers is rarely required, though some companies voluntarily designate riparian buffers of 5-m to 10-m wide after the trees are harvested to the stream edge (Boothroyd and Langer 1999). The limited number of published studies on the removal of riparian forests suggests that impacts can be severe on the stream environment and include increases in sedimentation, landslides, bank instability, stream temperature, and shifts in invertebrate community composition (Graynoth 1979, Baillie and others 1999, Collier and Bowman 2003).

In this study, we compared the implications of two riparian management scenarios on the supply of wood to a hypothetical stream located in the central North Island region of New Zealand. With the use of a simulation model, two riparian management options along with the influence of buffer width were considered. In the first option, the pines were harvested to the stream edge and a buffer of a given width was set aside from future harvest to allow native species to colonize. In the second option, pines were retained within a riparian buffer of a given width and excluded from future harvest, allowing native species to establish under the pine canopy.

Methods

Model Description

All simulations were conducted by linking OSU STREAMWOOD (Meleason 2001) with LINKNZ, a forest gap model designed to grow native forests of New Zealand (Hall and Hollinger 2000). Both models are individual-based stochastic models that operate to a yearly time step. LINKNZ is a forest ecosystem process model based on the eastern North American simulation model LINKAGES (Pastor and Post 1985, 1986). The model simulates successional sequences in the native forests of New Zealand from climate and soil attributes at a site and a set of parameters determined for 75 tree species known to play key roles in New Zealand forest ecosystems (Hall and Hollinger 2000, Hall and McGlone 2001). Because detailed descriptions and an evaluation of LINKNZ have been published elsewhere (Hall and Hollinger 2000), only an overview is provided.

LINKNZ shares the same underlying structure as most forest gap models (Botkin and others 1972, Shugart and West 1977) where recruitment, growth, and death of individual trees are simulated on fixed

size sample plots (1/12th ha in LINKNZ). The model was altered to produce an output file of all dead trees (≥ 10 cm DBH) by species, DBH, total height, year of death, and plot iteration number. In addition, LINKNZ was extended to grow *Pinus radiata* under plantation conditions, with user-defined initial variables that included initial tree density, target density, and year of a thinning cut. Tree species regeneration in the pine plantation can be suppressed for a given time period (year 10 for this study) to simulate the effects of plantation management, and thereafter all species become potential recruits on the plot. Management practices were assumed to reduce the mortality of pine to 10% of native forest for the first 10 years, based on plantation mortality rates in the region (New Zealand Forest Research Institute, unpublished data), after which the mortality rate was gradually increased over a 10-year period to reach that of species competing in a native forest ecosystem.

OSU STREAMWOOD was designed to simulate riparian forests of the Pacific Northwest and recruitment of trees to a stream, and to apply in-channel wood dynamics (breakage, movement, and decay) to individual logs. A detailed description of OSU STREAMWOOD has been published elsewhere (Meleason 2001).

For these simulations, forest tree mortality files produced by LINKNZ replaced output from the forest model contained within OSU STREAMWOOD. LINKNZ simulated forest development on 50 plots over an 800-year period, beginning from a cleared state. All riparian areas in the simulations covered 1 ha (50-m wide by 200-m long). For each iteration of a given simulation, twelve 1/12th-ha plots were randomly selected from fifty possible plots in the LINKNZ mortality file. The position of the trees (x-y coordinates selected from a random uniform distribution) and tree fall angle (selected from a random uniform distribution) differed among the riparian areas within a given iteration. The riparian buffer width for each simulation corresponded to the distance from the stream channel that trees could be recruited into the channel. Trees were assumed to fall the year they died. The chance of a tree entering the stream depended on the effective height of the tree (height of stems > 10 -cm diameter, assuming a conical form), distance to the channel, and angle of fall (Van Sickle and Gregory 1990). Trees that intersected at least one of the stream banks when they fell were subjected to tree entry breakage.

Tree entry breakage, as well as log breakage within the stream, has received very little attention, but its exclusion was found to produce unreasonable distri-

butions of length frequency (Van Sickle and Gregory 1990). To determine tree entry breakage, the number of breaks along a single tree was selected randomly from 0 to a maximum (set to 3 for these simulations). The location of the breaks was randomly selected from a normal distribution (mean break-location 60% from tree base, standard deviation 10% of effective tree length). Because breakage location was independent of stream banks, logs could be partially outside the channel. Logs completely outside the channel or of less than minimum dimensions (1-m length, 10-cm diameter) were removed from further analysis. The chance of in-channel log breakage was assumed to increase with stream residence time and decrease with an increase in log size (top diameter). Logs selected to break were broken at half the natural logarithm of their length.

The chance of log movement was assumed to increase with stream flow and decrease with the ratio of log length to bankfull width, number of key pieces (length $>$ bankfull width) within the reach, and proportion of the piece outside the channel. Stream flow was represented as an annual peak recurrence interval (between 1 and 100) with a lognormal random number distribution. The same flow regime was used in all simulations. The chance of movement function was set to represent streams with relatively low mean flood flow as is common in the central North Island of New Zealand (McKerchar and Pearson 1990). The distance-moved for selected logs was based on a single negative exponential equation where the reciprocal of the slope is the average travel distance (set to 10 bankfull widths for all simulations reported here).

Log decay in OSU STREAMWOOD represents mineralization (leaching and respiration) and physical abrasion from moving water. Limited information is available for decay rates of large wood in streams (Allan 1995). Completely submerged or buried logs can last for hundreds or even thousands of years (Guyette and others 2002), because microbial (Aumen and others 1983) and invertebrate (Tank and Winterbourn 1995, Collier and others 2004) colonization is mostly limited to the surface of the log. Log volume was decayed using the single exponential model (Olson 1963) with species-specific decay rate constants (Table 1). Decay constants used in this study were based on terrestrial decay studies of native species of New Zealand (Hughes 1982, Stewart and Burrows 1994) and elsewhere (Harmon and others 1986, Yin 1999), and aquatic decay studies in New Zealand (Collier and Baillie 1999, Collier and others 2004) and elsewhere (Diez and others 2002). Based on a previous assessment (Meleason 2001), the aquatic decay rate was assumed to be

Table 1. Decay rate constants and the percent of the total mean annual basal area available for recruitment to the channel from the two hypothetical forests

Taxa	Decay constant (yr ⁻¹)		Total mean annual basal area* (%)	
	Aquatic	Terrestrial	Native	Pine to native
Mixed conifers ¹	0.010	0.020 ^{b-c}	23.1	18.4
<i>Dacrydium cupressinum</i>	0.004 ^a	0.008 ^c	26.0	22.8
<i>Phyllocladus trichomanoides</i>	0.004	0.008 ^c	0.9	1.0
<i>Pinus radiata</i>	0.020 ^{a, f}	0.040 ^c	0.0	18.6
<i>Podocarpus totara</i>	0.002	0.004 ^c	3.4	3.9
Mixed hardwoods ²	0.010	0.020 ^{b-c}	12.7	7.1
<i>Beilschmiedia tawa</i>	0.020	0.040 ^c	2.4	4.7
<i>Elaeocarpus dentatus</i>	0.020	0.040 ^c	8.5	5.1
<i>Knightia excelsa</i>	0.100 ^a	0.200	7.9	6.8
<i>Laurelia novae-zelandiae</i>	0.020	0.040 ^c	2.3	4.2
<i>Nothofagus</i> spp.	0.002	0.004 ^g	3.2	0.2
<i>Weinmannia racemosa</i>	0.020	0.040 ^c	9.6	7.2

¹Mixed conifers includes the following species: *Dacrycarpus dacrydioides*, *Libocedrus bidwillii*, *Phyllocladus alpinus*, *Podocarpus hallii*, *Prumnopitys ferruginea*, and *Prumnopitys taxifolia*.

²Mixed hardwoods includes the following species: *Aristotelia serrata*, *Ascarina lucida*, *Elaeocarpus hookerianus*, *Griselinia littoralis*, *Hedycarya arborea*, *Ixerba brexioides*, *Kunzea ericoides*, *Lagarostrobos colensoi*, *Lepidothamnus intermedius*, *Leptospermum scoparium*, *Melicactus ramiflorus*, *Metrosideros robusta*, *Myrsine australis*, *Myrsine salicina*, *Nestegis cunninghamii*, *Pittosporum eugeniioides*, *Pseudopanax arboreus*, *Pseudopanax crassifolius*, *Pseudowintera axillaries*, *Quintinia acutifolia*, *Quintinia serrata*, *Schefflera digitata*, *Weinmannia silvicolica*.

^aBased on Collier and others (2004).

^bBased on Harmon and others (1986), Table 3.

^cBased on Hughes (1982), Table 1.

^dBased on Means and others (1985).

^eBased on Yin (1999), Appendix 2.

^fCalculated from Stewart and Burrows (1994).

^gDiez and others (2002).

*The total mean basal area is the sum across all years of the mean plot basal area that died in a given year.

half the terrestrial decay rate. The decay rate for a log partially in the channel was assumed to be between the aquatic and terrestrial rate and was based on the proportion of the log within the stream.

Modeling Scenarios

Simulations reported here represent a small forest stream in the central plateau of the North Island at an elevation of 450 m. This region is within an extensive volcanic zone, and the relatively low mean annual flood flows are attributed to high infiltration rates through the rhyolitic ash that covers the area (McKerchar and Pearson 1990).

Two forest tree mortality files for input to OSU STREAMWOOD were produced from separate simulations of forest development by LINKNZ (Figure 1A and B). The first simulation, referred to as "native forest," reproduced the lowland podocarp/hardwood forest type once common to the region (McEwen 1987) (Figure 1A). The second forest simulation, referred to as "pine to native forest," represented a newly established pine plantation in which all management activities were ceased at year 10, and native tree species were allowed to establish (Figure 1B).

Following normal management practice, initial planting density was 1000 stems per hectare and was thinned at year 8 to 400 stems per hectare. Because of the site elevation, productivity in the pine plantation was relatively low for the region. Other site characteristics that influenced stand productivity were soil-moisture capacity (field capacity 15.4 cm, wilting point 3.3 cm) and initially available soil N (1.43 t/ha). In addition, the forest model assumed that native tree species establishment within the pine plantation was not limited by the availability of native tree seed.

The stream system consisted of four reaches each 200 m long with a bankfull width of 4 m and a riparian forest on each bank. Total wood volume (volume of all logs intersecting at least one stream bank) from the farthest downstream reach was used in all analyses. The upper three reaches served as the upstream source of wood in fluvial transport to the lowest reach. The riparian forests were assumed to be the sole source of all wood to the stream, and the maximum buffer width of 50 m was assumed to be wide enough to include all tree recruitment to the stream (less than or equal to maximum obtainable effective tree height). Damage to the forest buffer and slash inputs to the stream during

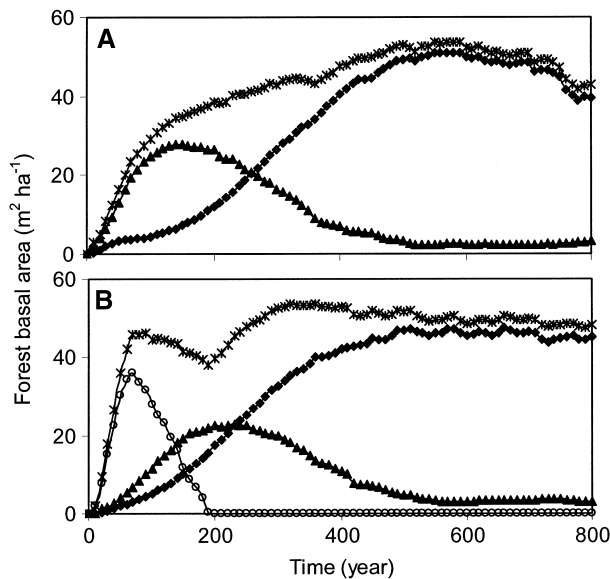


Figure 1. Composition of the hypothetical forests used in all simulations with (A) native forest and (B) pine plantation to native forest. (▲) Mixed hardwood, (◆) conifer, (○) *Pinus radiata*, and (*) total basal area.

harvest was assumed to be negligible, and wood within the channel was not removed after a harvest operation.

Two sets of simulations were conducted: one for the native forest and one for the pine to native forest transition. Each set consisted of six simulations that differed by the width of the riparian forest (5, 10, 15, 20, 25, and 50 m) that supplied all trees recruited to the stream. Each simulation consisted of 400 iterations of 800 years, each beginning with no wood in the channel.

Model Performance

We evaluated the modeling exercise in terms of the variability associated with linking the two stochastic models (model convergence test), reasonableness of model predictions (comparison of observational data with simulation results), and the relative importance of the in-channel processes on model predictions (sensitivity analysis).

A model convergence test (based on Bugmann and others 1996) was conducted with OSU STREAMWOOD using a LINKNZ forest input file to determine the minimum number of iterations required to capture the variation among iterations. A simulation was conducted for 2000 iterations of 800 years using a 50-m-wide native forest buffer. The population sampled for the convergence test was the total wood volume at year 800 from each of the iterations ($N = 2000$). A total of 13 sample sets were randomly selected from the pop-

ulation. Each sample set consisted of 10 samples with n values per sample, where n ranged from 10 to 600. The statistic (q) used to test for model convergence approaches a non-zero value as the sample size increases and does not assume that the sample distribution is normal (Bugmann and others 1996):

$$q = \frac{(P_{90} - P_{10})}{\text{median}} \quad (1)$$

where $(P_{90} - P_{10})$ is the interval between the 90% and 10% percentile. Percentiles were calculated using the Hazen formula (McBride 2005):

$$r = \frac{1}{2} + \frac{Pn}{100} \quad (2)$$

where r = percentile rank for the given percentile, P = given percentile, and n = number of samples.

We compared observational data with simulation results to provide sufficient evidence that the basal area of the native forest and the wood volume in the stream predicted by the model were reasonable for the central North Island region. The nearest pristine native forest is the Waihaha forest in the Pureora region west of Lake Taupo, which was classified as a rimu-dominated (*Dacrydium cupressinum*) dense, mixed, podocarp type (McKelvey 1963). The riparian forest and wood in the channel along a tributary of the Waihaha River (elevation of 550 m) was measured for a study on wood in native forest streams and will be reported elsewhere (Meleason and others, in preparation). The basal area estimate of the Waihaha forest was based on the measurement of the DBH (diameter at breast height of 1.37 m from the base) of all trees ≥ 10 cm within six 10-m-wide by 20-m-long (perpendicular to the stream) plots that were evenly spaced along a 200-m study reach. The volume of wood in the channel was based on the inventory of all logs ≥ 10 cm diameter and ≥ 1 m length and at least partially within the bankfull width within the 200-m study reach. Log shape was assumed to be conical and the volume of logs with complex shapes (e.g., treetops and branches) was estimated by dividing the log into measurable segments. We also compared the length class frequency distribution of the logs sampled at the Waihaha tributary with the length class frequency distribution predicted from native forest simulation using the 50-m-wide buffer.

The final model performance test conducted was a sensitivity analysis, which was done to determine the relative importance of selected model components on model outcomes. The single parameter sensitivity analysis method (reviewed in Haefner 1996) was chosen because it appears to be the most practical approach for stochastic models (Leemans 1991).

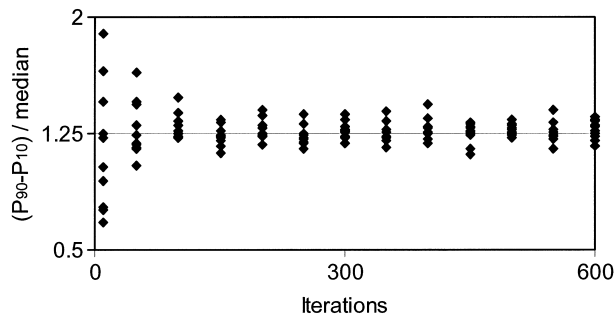


Figure 2. Convergence test results using total wood volume at year 800 randomly selected from a simulation of 2000 iterations of 800 years. Each of the 10 samples at each iteration was subjected to the test statistic where $(P_{90} - P_{10})$ is the interval between the 90% and the 10% percentile of the members of the sample. The horizontal line is the value of the test statistic for 2000 iterations.

Sensitivity index (S) is defined as the standardized change in the output over the standardized change in the input parameter:

$$S = \left[\frac{R_a - R_n}{R_n} \right] / \left[\frac{P_a - P_n}{P_n} \right] \quad (3)$$

where R_a and R_n are the adjusted and nominal output parameters and P_a and P_n are the adjusted and nominal input parameters (Haefner 1996). When $S = 1$, the percent change in output equals the percent change in input.

The sensitivity analysis was conducted on total wood volume and consisted of a set of simulations using the input files for each scenario modeled: native forest and pine to native forest. The 50-m-wide riparian buffer simulation for each of the hypothetical forests provided the nominal values for S . Simulations that provided the adjusted values were identical to their base simulation, except that output from one of the processes was increased by 10%. For example, if chance-of-movement for a given log was 10%, it would be increased to 11%. A total of five processes were subjected to the sensitivity analysis: entry breakage, chance of in-channel breakage, chance of movement, distance moved, and decomposition. The adjustment to decomposition was on the composite decay constant k for all species and for selected species to determine the influence of individual taxa on model output.

The overall sensitivity for a given variable was characterized using the maximum absolute value obtained ($|S|$). We also characterized the changes in S that occurred over the entire simulation using three sensitivity categories presented in Kercher and Axelrod (1984), defined as: insensitive ($|S| \leq 0.5$), sensi-

tive ($0.5 < |S| \leq 1.1$), and very sensitive ($|S| > 1.1$). The proportion of the 800-year time series ($n = 80$ using a 10-year time step) belonging to each of the three sensitivity categories was determined for each sensitivity simulation.

Results and Discussion

Model Performance Tests

For the model convergence test, a plot of iteration n (n used in each sample for a given set of samples) by the q statistic was visually inspected for the number of iterations required to converge to the value of q calculated from the entire population ($n = 2000$) (Figure 2). Variability of the test statistic q declined from a CV (coefficient of variation) of 35% at 10 iterations to a CV of <5.5% for ≥ 150 iterations (Figure 2). These results suggest that a minimum of 150 iterations would be required to make reliable estimates of the mean wood volume using OSU STREAMWOOD with the LINKNZ forest files.

Riparian forest basal area and the total wood volume in streams of the same forest type have been found to be highly variable (Harmon and others 1986, Meleason and others in preparation). The mean live tree basal area at the Waihaha forest was $69 \text{ m}^2 \text{ ha}^{-1}$ with a 95% confidence interval of 18 to $121 \text{ m}^2 \text{ ha}^{-1}$. Mean basal area for conifer measured at the Waihaha forest ($53 \text{ m}^2 \text{ ha}^{-1}$, 95% confidence interval of 6 to $100 \text{ m}^2 \text{ ha}^{-1}$) was very similar to the simulated native forest (e.g., $51 \text{ m}^2 \text{ ha}^{-1}$ at year 550) (Figure 1A) and the simulated pine to native forest (e.g., $47 \text{ m}^2 \text{ ha}^{-1}$ at year 550) (Figure 1B). The greatest difference between simulated and observed forest occurred in mixed hardwood basal area, which was $16 \text{ m}^2 \text{ ha}^{-1}$ at Waihaha forest (95% confidence interval of 4 to $28 \text{ m}^2 \text{ ha}^{-1}$), and was $3 \text{ m}^2 \text{ ha}^{-1}$ in the simulated forests by year 800 (Figure 1A and 1B).

The total wood volume measured at the Waihaha tributary (3.7 m bankfull width, $49 \text{ m}^3 \text{ 100 m}^{-1}$ of stream length) was 22% greater than the maximum simulated from the native forest (total volume of $38 \text{ m}^3 \text{ 100 m}^{-1}$, standard deviation = $17 \text{ m}^3 \text{ 100 m}^{-1}$ at yr 780), and 37% greater than the maximum simulated from the pine to native forest ($31 \text{ m}^3 \text{ 100 m}^{-1}$ at yr 780, standard deviation = $16 \text{ m}^3 \text{ 100 m}^{-1}$). The tree fall regime for all simulations was assumed to be random, although a tree fall regime that has a slightly greater chance of falling towards the channel than away from it can have a tremendous influence on wood volume delivered to the channel (Van Sickle and Gregory 1990, Meleason and others 2002). In this case, the observed total volume in the Waihaha tributary was between a simulation with a random fall regime (38 m^3

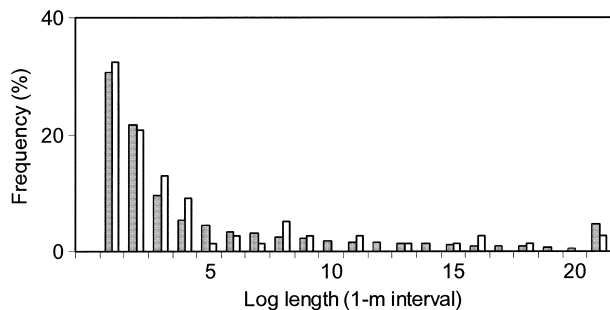


Figure 3. Length frequency distributions for simulated (shaded bars) and observed (open bars) populations of logs in the stream. The simulated distribution is from year 800 of the native forest simulation with a 50-m riparian forest source area, and the observed is from an old-growth forest tributary of the Waihaha stream. The last log-length category includes all logs ≥ 21 m.

100 m^{-1}) and a simulation where all trees fall directly towards the channel ($116 \text{ m}^3 100 \text{ m}^{-1}$). This suggests that a tree fall regime with a slightly greater chance of falling towards the channel than away from it could easily account for the difference between the observed and simulated total wood volumes. In addition, the greater basal area of mixed hardwoods in the Waihaha forest than simulated for the native forest may also account for some of the difference.

The ability of the model to predict an observed characteristic of the system such as the length frequency distribution is another type of performance assessment. The length class frequency distribution of the logs in the stream reflects the collective history of breakage events on trees entering the stream and logs within the channel (Meleason 2001). A reverse-J length frequency distribution has been observed for logs in old-growth forest streams (e.g., Richmond and Fausch 1995, Berg and others 1998). The comparison of the length frequency distributions between native forest buffer simulation (year 800 of the 50-m-wide) and the field study at Waihaha stream indicated that the simulated results are consistent with the observed results overall (Figure 3). The two distributions were also compared using the Komogorov-Smirnov test and found no evidence that the two samples were drawn from different distributions (p value = 0.37, $n = 21$).

For the sensitivity analysis, the model's general response to a 10% increase in the nominal value of the processes tested was a slight reduction in total stream wood volume through time. Decomposition was the most sensitive of the five processes tested on both forest types, and tree entry breakage was the least sensitive (Table 2). For the native forest, the time interval when decomposition had its highest sensitivity scores (years

130–240) also included the time period when the other process-level parameters (chance of breakage, chance of movement, and distance moved) were also at their greatest sensitivity (classified as “sensitive”). This period also coincided with the most sensitive period for mixed hardwoods and was likely to be due to the shorter tree heights and greater decay rates of the hardwoods as compared to the conifer species (especially *D. cupressinum*), which dominate the later portion of the simulation.

The time period in which decomposition had its highest sensitivity scores in the pine to native forest test (years 180–250) was shorter than in the native forest test. Apart from entry breakage, this short interval coincided with the most sensitive period of the other processes tested, as well as that for the decomposition of mixed hardwood and mixed conifer species (classified as “sensitive”). The model was less sensitive when the initial forest was dominated by pine rather than mixed hardwood, due most likely to the larger size of pine relative to the hardwood species. The results of the sensitivity analysis from both forest types suggested that the most sensitive time period was prior to dominance by the native conifers (around year 250), regardless of initial forest composition (e.g., pine or native hardwoods).

Sensitivity analyses can also detect changes in the timing of events in the output series under investigation (Botkin and Nisbet 1992). Although the magnitude of the total wood volume was influenced by changes in the input parameters, the timing of minimum and maximum values and the shape of the total wood volume graphs were barely affected. Maximum total wood volume in the native forest simulations was at 780 years, regardless of the process perturbed in the sensitivity analysis. For the pine to native forest simulations, the timing of the first peak at 100 years, the minimum at 250 years, and second maximum at 600 years in the base simulation was almost identical to the adjusted cases. This suggested that although the actual wood volumes predicted by the model were sensitive to the underlying parameter values of the processes tested, the timing and general shape of the output graphs remained unchanged.

Total Wood Volume from the Native Forest Simulations

The first set of simulations, utilizing the native forest tree mortality file from LINKNZ, varied the width of the riparian forest buffer (5, 10, 15, 20, 25, and 50-m wide) contributing trees to the stream (Figure 4A and B). In general, wider buffers produced greater wood volumes, and as the forest aged, differences in volumes

Table 2. Summary of the single parameter sensitivity analysis* using a 10% increase of the nominal value for selected processes

Process tested	Native forest ^a			Pine to native forest		
	Maximum S (yr)	0.5 > S ≤ 1.1 (% time)	S > 1.1 (% time)	Maximum S (yr)	0.5 > S ≤ 1.1 (% time)	S > 1.1 (% time)
Process level						
Entry breakage ^b	-0.48 (600)	1.3	0.0	-0.51 (190)	1.3	0.0
Chance of breakage	-0.83 (240)	15.0	0.0	-0.76 (200)	13.8	0.0
Chance of movement	-0.88 (260)	25.0	0.0	-0.71 (220)	16.3	0.0
Distance moved	-0.82 (220)	21.3	1.3	-0.76 (230)	8.8	0.0
Decomposition ^c	-1.46 (200)	48.8	15.0	-1.67 (200)	40.0	8.8
Decomposition of selected taxa						
Mixed conifers ^d	-0.70 (260)	17.5	0.0	-0.6 (200)	11.3	0.0
<i>Dacrydium cupressinum</i>	-0.58 (800)	13.8	1.3	-0.57 (420)	6.3	0.0
<i>Pinus radiata</i>	NA	NA	NA	-1.46 (190)	20.0	10.0
Mixed hardwoods ^d	-1.03 (140)	31.3	0.0	-0.96 (200)	18.8	0.0
<i>Elaeocarpus dentatus</i>	-0.78 (800)	22.5	1.3	-0.81 (190)	8.8	0.0
<i>Knightia excelsa</i>	-0.74 (230)	17.5	1.3	-0.56 (190)	8.8	0.0
<i>Weinmannia racemosa</i>	-1.11 (230)	23.8	1.3	-0.85 (400)	8.8	0.0

*The sensitivity index (S) was based on total wood volume in the most downstream reach. The summary for each process includes the maximum absolute value of S (|S|) and corresponding year obtained by each process and the proportion of the simulation run (percent of the 800-year time series) categorized as “sensitive” (0.5>|S| ≤ 1.0) and “very sensitive” (|S|>1.0).

^a“Maximum” excludes S values from simulation years ≤ 30 because the low total wood volumes (<0.04 m³ 100 m⁻¹) produced uncharacteristically large values relative to the rest of the time series. However, all years were included in the ‘sensitive’ and ‘very sensitive’ columns.

^bMaximum number of entry breaks was increased from 3 to 4.

^cSensitivity applied to the composite decay constant of all species.

^dSee Table 1 for the list of species included in mixed conifers and mixed hardwoods.

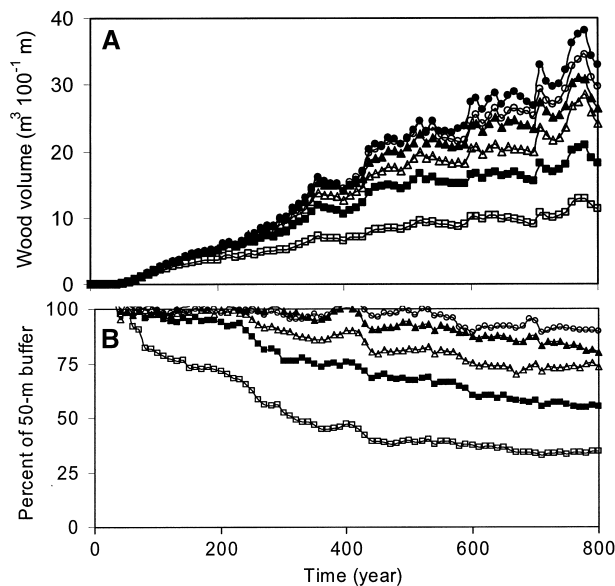


Figure 4. Total wood volume associated with the channel by buffer width for the native forest expressed as (A) m³ 100 m⁻¹ of stream length and (B) as a percentage of wood volume from the 50-m-wide native forest. Symbols represent riparian buffer widths of (□) 5-m, (■) 10-m, (△) 15-m, (▲) 20-m, (○) 25 m, and (●) 50 m.

increased between buffers (Figure 4A). However, for a given forest age, the increase in wood volume diminished as buffer width increased. This relationship was consistent with observed source distances (McDade and others 1990), since for a given tree height the probability of entering a stream decreases as distance to the stream increases (Van Sickle and Gregory 1990).

For all native forest simulations, recruitment to the stream was limited for the first 70 years (<1 m³ 100 m⁻¹) (Figure 4A). The paucity of wood in streams adjacent to young forests has been observed elsewhere (Grette 1985, Andrus and others 1988). In this native forest case, the early stages of forest development were dominated by mixed hardwood species, which reached maximum basal area at year 140, and subsequently replaced by slower growing conifer species (Figure 1A).

After the first 70 years, wood volume from the 5-m riparian zone approached 90% of that in the 50-m riparian zone (Figure 4B). By year 310, wood volume from the 5-m forest buffer was less than 50% of the 50-m buffer and varied between 33% and 40% from years 440 to 800 (Figure 4B). This suggests that the buffer width, as opposed to tree height, limited wood volume from the 5-m buffer from the earliest stages of stand development.

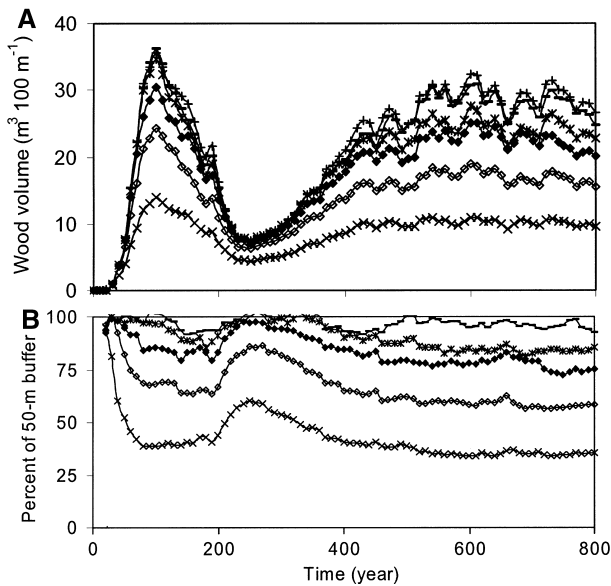


Figure 5. Total wood volume associated with the channel by buffer width for the pine to native forest expressed as (A) $\text{m}^3 100 \text{ m}^{-1}$ of stream length and (B) as a percentage of wood volume from the 50-m-wide native forest. Symbols represent riparian buffer widths of (x) 5-m, (◇) 10-m, (◆) 15-m, (*) 20-m, (—) 25-m, and (+) 50-m.

The wood volume from the 10-m forest buffer was 90% or more of that from the 50-m forest buffer for the initial 240 years, but was between 55% and 60% of the 50-m forest buffer for the last 200 years simulated (Figure 4B). Wood volumes from the 15-m and 20-m forest buffers were 90% or more of the wood volume from the 50-m forest buffer for the initial 300 and 570 years, respectively, but between 70% to 75% and 80% to 88% of the 50-m wood volume, respectively, for the last 200 years simulated (Figure 4B). These forests took longer to fully exploit the wider buffers because the height of the emergent layer of the stratified canopy, composed of *D. cupressinum*, reached an effective maximum height of 46.5 m by the end of the simulation.

The wood volume from the 25-m buffer was 89% or more of the wood volume from the 50-m buffer throughout the entire simulation, and 95% or more for the first 570 years simulated (Figure 4B). This suggests that the 25-m buffer width was not limiting the supply until the later stages of forest development (>570 years) when buffer widths between 25 m and 50 m contributed only 5% to 11% of the total wood volume of the 50-m buffer. Maximum wood volume from the 50-m buffer was $38 \text{ m}^3 100 \text{ m}^{-1}$ at year 780, and a significant linear trend (slope and intercept p values <0.0001) existed over the entire time series (volume = $0.047^* \text{ year} - 2.8$,

$r^2 = 0.98$). This linear relationship suggested that the recruitment rate exceeded the depletion rate for most of the simulation.

Total Wood Volume from the Pine to Native Forest Simulations

The second set of stream wood simulations, utilizing the pine to native forest input file from LINKNZ, varied the buffer width of the riparian forest (5, 10, 15, 20, 25, and 50-m wide) that contributed trees to the stream (Figure 5A and B). In general, the wood volume followed a bimodal distribution over time (Figure 5A) caused by the senescence of pine during the initial 200-year period, followed by an eventual dominance by native conifers (Figure 1B). The peak in pine basal area at year 70 (Figure 1B) and the subsequent sharp peak in wood volume at year 100 declining to a minimum around year 250 indicated that the depletion rate of pine wood in the channel exceeded the recruitment rate by native hardwoods and conifers (Figure 5A). By year 30, a common age for commercial harvest, the amount of wood in the stream was minimal ($<1 \text{ m}^3 100 \text{ m}^{-1}$) for all forest buffer widths (Figure 5A).

For stands older than 30 years, wood volume from the 5-m buffer was less than 90% of that from the 50-m buffer, which suggests that, in general, buffer width and not tree height limited tree recruitment. At year 100, wood volume in the 50-m buffer peaked ($36 \text{ m}^3 100 \text{ m}^{-1}$), and buffers at most 15 m wide restricted supplies of wood volume to the stream (5 m was 39%, 10 m was 68%, 15 m was 85% of the 50-m buffer wood volume). The post-pine minimum wood volume around year 250 was 21% of the maximum at year 100 and 23% of the maximum at year 600 for the 50-m buffer simulation. All but the 5-m and 10-m buffers (which were 60% and 86% of the maximum, respectively) had more than 90% of the wood volume of the 50-m buffer at year 250 (Figure 5B). This suggests that during the transition from pine to native species it was canopy height and not buffer width that limited the wood volume in the stream.

For stands older than 250 years, wood volume formed a broad peak, which reached a pronounced maximum in the 50-m buffer of $32 \text{ m}^3 100 \text{ m}^{-1}$ around year 600 and gradually declined to around $27 \text{ m}^3 100 \text{ m}^{-1}$ by the end of the simulation (Figure 5A). Wood volume of the 25-m buffer was more than 90% of that of the 50-m buffer for the entire simulation, suggesting that the contribution from buffers wider than 25-m played a minor role in producing the second peak in wood volume (Figure 5B). For the remaining buffer widths, wood volume (relative to the 50-m buffer) was stable for the last 200 years of the simulations, with the

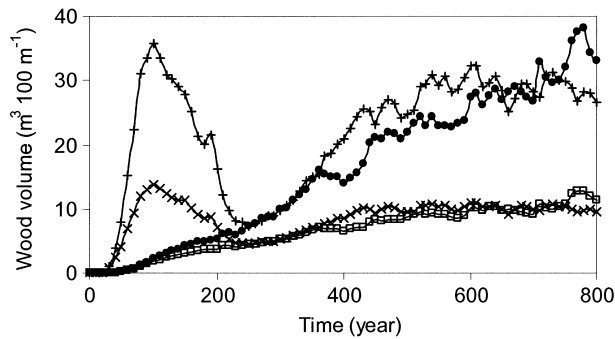


Figure 6. Total wood volume associated with the channel from the minimum (5-m) and maximum (50-m) buffer widths for the native forest and the pine to native forest buffers. Symbols represent (□) 5-m-wide and (.) 50-m-wide native riparian forest, and (×) 5-m-wide and 50-m-wide (+) pine to native forest.

5-m, 10-m, 15-m, and 20-m buffers producing around 35%, 58%, 77%, and 84% of the wood volume of the 50-m buffer, respectively (Figure 5B). This finding suggests that the wood volume from buffers at most 20 m wide and forest aged 600 or more years was limited by buffer width and not tree height.

Comparison of Native and Pine to native Forest Simulations

Under the native forest simulations, the buffer width required to include all recruitable trees to the stream increased as the forest aged because the emergent canopy height steadily increased throughout the entire simulation. A common emergent canopy species observed in these forests, *D. cupressinum*, is one of the tallest New Zealand tree species (Hinds and Reid 1957). However, it should be noted that the canopy height of forests might not always increase with age because late successional species may be shorter than the species replaced (Meleason and others 2003). The recruitment of pine to the stream from the pine to native forest produced considerably more wood volume than the native forest for stand ages less than 250 years (Figure 6), and this difference was primarily due to the greater height of the pines (e.g., at year 30, the maximum effective height of pine was 13 m vs. 6 m for mixed hardwoods). The greatest difference between the forests occurred at year 100, when the pine to native forest had eight times the wood volume from the 5-m buffer and 16 times the wood volume from the 50-m buffer than the native forest (Figure 6). At year 250, the wood volume from the 50-m buffer from both forest types was similar. This suggests that the pine to native forest could provide much more wood much earlier than the native forest in early successional stages.

The wood volume from the pine to native forest was slightly greater than from the native forest between 370 and 640 years (average of $4.8 \text{ m}^3 \text{ 100 m}^{-1}$) and was slightly less than the native forest for the remaining portion of the simulation (Figure 6). This suggests that the long-term supply of wood from the pine to native forest is similar to the long-term supply of wood provided by the native forest.

Management Implications

The results of this study indicated that the pine-plantation-to-native forest buffer provided the greater supply of wood to the stream over the short term and comparable amounts of wood over long-term time scales. Studies on the ecological role of wood in streams suggest that wood from non-native tree species was functionally indistinguishable from native species. For example, in pine plantation streams in the central North Island of New Zealand, local variations in habitat and wood surface texture appeared more important rather than any distinction between native and non-native species for the colonization of epixylic biofilm and utilization by invertebrates (Collier and others 2004).

Our simulations suggest that native forest buffers, cleared of their original tree cover, required ~ 70 years before wood was recruited to the stream, due mainly to the relatively slow growth of the native species compared to the exotic pine species. Because of the moderate climate, a high proportion of the native tree species modeled could potentially establish on the cleared site. As a consequence, seedling and sapling mortality rates were higher and overall forest growth was slower during the first 70 years due to the effects of intense competition for available light, soil nutrients, and soil moisture. Although the young native forest did not provide a large supply of wood to the stream, it can still provide important ecological functions such as small-wood and leaf litter input to the stream, bank stabilization, and shading influencing water temperature, and habitat for birds and insects.

Finally, the composition of the native forest may differ from that simulated because the time frame to establish New Zealand native forest tree species is strongly influenced by distance from propagule source (Hall and Meurk, in preparation). *Nothofagus* species rely on wind dispersal to distribute propagules over distances more than 100 m from the nearest source, and most New Zealand conifer species are primarily dispersed by avian fauna. In areas isolated by several kilometers from forest fragments, these mechanisms tend to produce a low probability of

initial establishment, in which case, an under-planting of selected shade-tolerant dominant species, at intervals ranging from 100 m to 1 km, would assist to promote and accelerate the realization of native forest similar in structure to mature forest fragments in the region.

Limitations of This Study

This study explored the long-term implications of riparian management practices on wood volume in streams, without exploring impacts from major episodic disturbances that are common in the New Zealand landscape (e.g., fire, wind-throw, landslide, volcanic activity, and infestation by a forest pathogen). An analysis of the effects from such episodic events on the long-term implications of the various riparian management strategies was beyond the scope of this study. Disturbances can alter patterns of recruitment of wood to the stream due to interruptions in the pattern of forest succession (e.g., Hall and Hollinger 2000, Hall and McGlone 2001). For instance, a simulation experiment conducted for riparian forests in the Intermountain West region of the USA found that the wood volume in the stream increased substantially after a stand-replacement disturbance (fire or insect infestation) and then declined below the long-term average as the new forest matured (Bragg 2000), which is consistent with low inputs from the young native forest reported here.

Conclusion

New Zealand is not unique in utilizing tree plantations composed of a single exotic species such as *Pinus radiata* for timber production (Lewis and Ferguson 1993) or harvesting forest plantations to the stream edge. After harvesting, the recovery of riparian functions such as the recruitment of wood to the stream can require periods ranging from decades to centuries. This study suggests that excluding a portion of the plantation forest adjacent to the stream from future harvests could enhance the short-term recruitment of wood to the stream as compared to the recruitment provided by the re-establishment of a native forest after a harvest to the stream edge. In addition, the designated pine buffer would provide conditions that favor the re-establishment of the more shade-tolerant native species, which eventually become the long-term source of wood to the stream. Buffer width was found to be an important factor in determining wood recruitment, and the model simulations suggest that buffer widths less than maximum tree height will limit the supply of wood to the channel.

We have focused specifically on the supply of wood to the stream, and have noted that the presence of riparian buffers can offer numerous additional benefits to both the terrestrial and aquatic environment. Indeed, the inclusion of riparian buffers has become a common element in many riparian management plans to mitigate the impacts of various land uses on stream ecosystems. We recognize that such buffers are not sufficient alone and that several other mitigating measures are required to reduce the ecological impact of streamside harvest operations. However, we would argue that the formation of riparian buffers should be considered to offset the effects of forest harvest on the aquatic environment.

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