HARVESTING EFFECTS ON WOODY DEBRIS AND BANK DISTURBANCE IN STREAM CHANNELS

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ABSTRACT

Woody debris volumes and channel bank disturbance were measured in a 100-m section of stream channel, prior to and after harvesting, in 17 streams in pine plantations in five regions of New Zealand. These sites were harvested using four different harvest methods. Volumes of pre-harvest woody debris and woody debris produced during harvest averaged 105 m^3/ha, and 147 m^3/ha, respectively. Apart from the stream-cleaned sites where virtually all the pre-harvest and harvest woody debris was removed, post-harvest volumes (pre-harvest + harvest) averaged 289 m^3/ha and increased three-fold on average over pre-harvest levels. Most of the woody debris in the stream channel was positioned above the stream—69% of pre-harvest woody debris, 64% of harvest woody debris, and 66% of total post-harvest woody debris. The remainder lay in-stream or on the floodplain. The most significant change in woody debris characteristics after harvest was size distribution. Small woody debris <10 cm in diameter (SWD) increased from 13% of woody debris volumes at pre-harvest to 38% at post-harvest. The number of pieces of large woody debris ≥10 cm in diameter (LWD) increased significantly, and the average length and piece size decreased significantly after harvest. This was due mainly to the removal of the larger merchantable pieces of LWD from the stream channel.

Harvest method had the most impact on harvest woody debris volumes in the stream channel, overriding the influence of riparian buffers which ranged in width from 1 to 30 m at four of these sites. Stream-cleaned sites had the lowest harvest woody debris volumes, followed by sites harvested with ground-based systems (15 m^3/ha and 48 m^3/ha respectively). When yarder systems were used to extract timber back from the stream edge, woody debris volumes averaged 104 m^3/ha, whereas hauling across the stream channel resulted in the highest average woody debris volumes of 287 m^3/ha. For hauling across the stream channel only, there was a relationship between stand volume and harvest woody debris volumes.

Bank collapses accounted for 68% of all pre-harvest channel bank disturbances. Bank scuffing from felling and log extraction during harvest operations was the most common channel bank disturbance after harvest (46%). Harvest method did not show a clear relationship with the degree of channel bank disturbance.

Keywords: harvesting; woody debris; large woody debris; channel bank disturbance; pine plantations; *Pinus radiata*.

INTRODUCTION

In natural forests, woody debris in the stream channel is usually sourced from windthrow, bank under-cutting, or mass movement (Swanson *et al.* 1976; Sedell *et al.* 1988). This woody debris can have a strong influence on the hydraulics, channel morphology, and ecological processes of forested streams (Swanson *et al.* 1976; Harmon *et al.* 1986; Sedell *et al.* 1988; Abbe & Montgomery 1996).

The larger, more stable, woody debris can form steps in the channel profile, slowing and diverting stream flow, forming pools, and increasing the diversity and complexity of habitat in the stream ecosystem for aquatic animals (Harmon *et al.* 1986; Sedell *et al.* 1988; Evans *et al.* 1993). Woody debris accumulations also provide important storage sites for sediment and organic material, slowing its movement through the stream ecosystem (Bilby & Likens 1980; Mosley 1981; Harmon *et al.* 1986; Bilby & Ward 1989).

Harvesting operations have the potential to change the amount and characteristics of woody debris in streams and increase channel bank disturbance. In a number of North American studies, past harvesting practices tended to decrease wood volumes in the stream channel (Froehlich 1977; Toews & Moore 1982a; Hogan 1987). Woody debris piece size distribution also changed. After harvest, piece size was smaller, the number of pieces increased, and the woody debris was less stable.

Harvesting operations can also increase the amount of channel bank disturbance. Toews & Moore (1982b) recorded significant increases in channel bank erosion in harvested sites in comparison to sites where unharvested riparian buffers remained.

In the pine plantations of New Zealand, harvesting residue is the main source of woody debris in the stream channel, although some additional woody debris enters the stream channel from thinning operations and windthrow. Woody debris from harvesting operations can provide shade, temperature control, and a habitat and food source for some aquatic animals where benthic substrates are unsuitable (Collier *et al.* 1997). However, high levels of woody debris can affect water quality (C.Pruden & C.Coker unpubl. data; K.J.Collier, E.J.Bowman, & J.N.Halliday unpubl. data) and in areas which are subject to frequent flooding, woody debris can be a potential hazard to on-site and downstream infrastructures.

Harvesting in New Zealand is carried out on a range of terrain types and under diverse regulatory and forest company rules. This has resulted in the use of a wide range of systems and practices as regards harvesting along stream edges. The initial part of this study measured woody debris characteristics in 24 stream sites around New Zealand, prior to harvest (Baillie *et al.* 1999). Seventeen of these sites were re-measured after harvest. Follow-up measurements at the remaining sites were not completed because of harvest schedule changes and flooding.

The objective of this part of the study was to quantify the effect of harvesting systems and practices on woody debris characteristics and channel bank disturbance in streams within pine plantations.

METHOD

Study Sites

Characteristics of the sites are summarised in Table 1. The first- to third-order streams (Strahler 1957) ranged in width from 0.5 to 5.5 m. Sixteen sites were in stands of *Pinus radiata* D. Don ranging in age from 22 to 34 years. One site (Site 7) was in a *Pinus nigra* Arn. stand aged 68 years. Four sites (sites 4, 5, 13, and 16) had riparian areas of native trees, shrubs, and ground ferns, ranging from 1 to 30 m in width along the stream edge (Table 2). All sites were clearfelled; 12 sites were harvested using yarder systems, the other five sites were harvested with ground-based systems.

No harvesting occurred within the riparian buffers. Any woody debris introduced into the stream from the riparian buffers during harvesting, was a result of damage to the riparian vegetation during the felling and extraction of timber from the site.

Each site was classified into one of four harvesting methods, using the harvesting system and prescription information supplied by the forest companies:

Method 1 - stream clean: motor-manual felling, yarder systems used to haul the timber across or back from the stream channel, all woody debris (pre-harvest and harvest woody debris) was manually removed from the stream channel.

Method 2 - ground-based: trees were directionally felled and extracted away from the stream edge using either motor-manual felling, tractors, or excavators.

Method 3 - haul back from stream edge: motor-manual felling, where possible directional felling away from the stream edge, yarder systems used to extract timber back from the stream channel.

Method 4 - haul across stream channel: motor-manual felling, where possible directional felling away from the stream edge, yarder systems used to extract timber across the stream channel.

Timing of Pre- and Post-harvest Measurements

To minimise the effect of high flows or flooding on the woody debris characteristics and channel bank disturbance, pre-harvest measurements were made immediately prior to harvest and post-harvest measurements were completed as soon as possible after harvest. If harvesting was delayed, sites were rechecked and where necessary the pre-harvest measurements re-done if there was any evidence of changes in the stream channel.

If high flows occurred after harvest and before the post-harvest measurements were completed, then the site was excluded from the study. Other reasons that sites were excluded from the study were: delays in harvesting, a mixture of ground-based and yarder systems used to harvest the site, and at one site a log bridge was put in across the stream. As a result of these factors, of the 24 sites that were measured prior to harvest, only 17 were successfully re-measured after harvest.

Woody Debris and Channel Bank Disturbance Measurements

At each site, a representative 100-m section of stream channel was selected for the study. Prior to harvest, channel morphology measurements were taken (Fig. 1) and used to calculate the area of the stream channel for use in subsequent woody debris volume calculations.

TABLE 1–Description of study sites.

Region and geology*	Soils†	Catchment area (ha)	Av. stream width (m)	Av. stream depth (mm)	Stream order
Auckland/Coromandel					
Sandstone/mudstone	Ultic	16.4	1.4	68	1
Andesite	Brown (brown granular clays)	65.0	3.6	155	1
Andesite	Brown (brown granular clays)	68.5	3.2	36	1
Andesite	Brown (brown granular clays	20.0	1.7	107	1
Rhyolite	Brown	26.3	1.5	49	2
Central North Island					
Greywacke	Pumice	1150	5.1	316	3
Ignimbrite	Pumice	297	2.5	159	2
Ignimbrite	Pumice	268.5	2.5	171	3
Rhyolite/pumiceous alluvium	Pumice	2200	5.5	351	3
Ignimbrite	Pumice	865	1.4	479	2
Ignimbrite	Podzol	560	2.2	281	2
Rhyolite	Pumice	28.3	1.1	44	1
Hawke's Bay					
Sandstone/siltstone	Pumice	185	2.8	166	3
Alluvial sediment/ greywacke/ conglomerate & sandstone	Oxidic (sandy silts developed in pumice)	280	2.4	190	2
Nelson					
Greywacke/schist	Brown (yellow brown earths)	33.5	1.7	48	1
Greywacke/ schist	Brown (yellow brown earths)	63.5	2.6	61	1
Limestone/sandstone/ siltstone	Orthic brown soils	24.6	0.8	118	1
Gravels/ conglomerates	Brown (orthic brown soils)	16.7	2.6	6	1
Granite	Brown	26.5	3.0	45	1
Granite	Brown	9.3	2.6	46	1
Southland					
Sandstone/siltstone/ mudstone	Brown (yellow-brown earth/ silt loam	84.0	2.2	75	2
Schist	Pallic	458.0	2.3	109	3
Sandstone/siltstone	Brown	188.5	1.7	61	2
Siltstone/sandstone	Brown (sandy/ silty loams)	18.5	0.5	15	1

* Department of Scientific and Industrial Research (1972a,b).
† Hewitt (1995); Rijkse & Hewitt (1995).

Pre-harvest woody debris measurements were obtained using stratified sampling. Two strata were used to reduce the statistical error, the first consisting of small woody debris in

TABLE 2–Description of harvesting, stand, and riparian buffer characteristics.

Site No.	Stand volume (m^3/ha)	Ground slope (°)	Riparian characteristics: width and main vegetation type
Method 1—stream-clean			
1	579	26	
2	690	28	
3	690	20	
Method 2—ground-based			
8	720	3	
9	937*	3	
10	358	5	
12	412	19	
16†	663	3	1–30 m: wineberry (*Aristotelia serrata* (Forst.) Oliver) and fuschia (*Fuchsia excorticata* (Forst. f.) L. f.)
Method 3—haul back from stream edge			
5†	466	16	1–30 m: podocarps, native shrubs, and ferns
7	749	29	
Method 4—haul across stream channel			
4†	649	29	15–25 m: native shrubs
6	749	32	
11	571	13	
13†	241	31	25 m: beech (*Nothofagus* sp.)
14	522	29	
15	516	20	
17	561	15	

* *Pinus nigra* stand
† Riparian buffer present

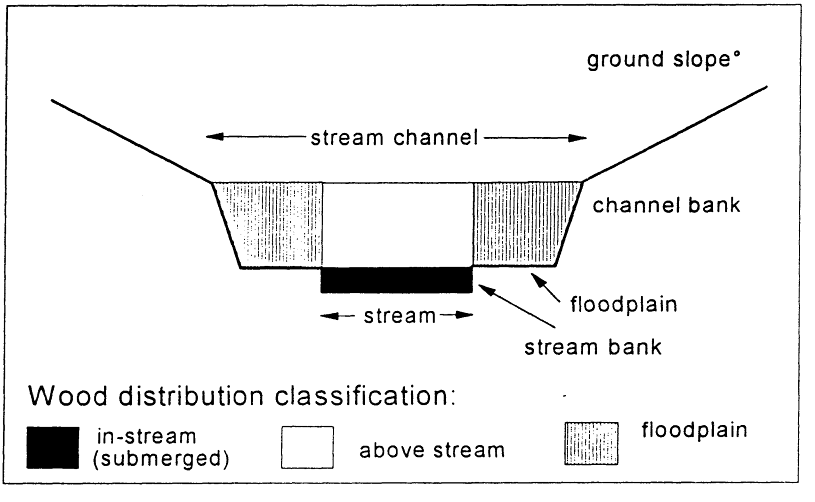

FIG. 1–Channel morphology measurements and classification of wood distribution in the stream channel.

the 1- to 9-cm diameter classes (SWD), the second consisting of large woody debris ≥10 cm in diameter (LWD). Transects based on the Van Wagner (1968) method were used to measure SWD. These were randomly orientated at 5-m intervals up the 100-m section of stream channel. All the LWD in the 100-m section of stream channel was measured for small-end diameter (s.e.d.), large-end diameter (l.e.d.), and length. SWD and LWD were classified as in-stream, above stream, or on the floodplain (Fig. 1). Details of the methodology have been given by Baillie *et al.* (1999).

Fresh channel bank disturbances were categorised according to the classifications in Table 3. Pre-harvest channel bank disturbances were classified as bank collapse, bank slump, or lateral scour. Post-harvest channel bank disturbances include two additional categories for harvest disturbance—bank scuff and ruts. The location of the channel bank disturbance along the 100-m section of stream channel was recorded. The length and height of each disturbance were measured and, where discrete volume losses had occurred, depth measurements were also taken to estimate volume. These records were used to ensure fresh channel bank disturbances at pre-harvest were not confused with any post-harvest channel bank disturbances.

TABLE 3–Classification of channel bank disturbances

Code	Channel bank disturbance description
BC	Bank collapse (discrete volume loss)
SL	Bank slump (no discrete volume loss)
LS	Lateral scour, stream flow has cut into bank, includes undercut banks
Direct harvest disturbance	
BS	Bank scuff from harvesting operation, may include discrete volume loss
R	Rut caused by harvesting operation, includes discrete volume loss

After harvest, virtually all the pre-harvest woody debris still remained in the stream channel, except in the stream-cleaned sites (1, 2, and 3) where nearly all the pre- and post-harvest woody debris had been removed. Only the additional woody debris introduced into the stream channel from harvesting, that could be easily identified by its freshness, was measured along with any additional channel bank disturbances.

Analysis

SWD volumes for the transects were calculated using the Van Wagner (1968) equation;

$$V = \Pi^2 \Sigma d^2 / 8L$$

where V = volume of wood (m^3/ha)
d = piece diameter (cm)
L = length of transect line (m)

Note that if piece diameters are measured in centimetres, and the transect line is measured in metres, the resulting volume is in cubic metres per hectare.

The volume of each piece of LWD was calculated using the three-dimensional formula of Ellis (1982);

$$V_{piece} = \exp[\,1.944157 \ln l + 0.029931\,(d) + 0.884711 \ln (D–d)/l - 0.038675] + 0.078540\,(d^2\, l)$$

where V_{piece} = volume of piece (m^3)
D = large-end diameter (cm)

d = small-end diameter (cm)
l = length of piece (m)
exp = antilog
ln = natural log

The volumes of the individual LWD pieces were totalled to give the LWD (m^3) for the 100 m of stream reach. This was converted to cubic metres per hectare, using the stream and floodplain widths along the 100-m section of stream channel to calculate the channel area. The SWD and LWD volumes were added together to give the total woody debris volume for the site.

A modification of the Van Wagner equation was used to calculate surface area for the SWD (Wallace & Benke 1984);

$$SA = (\Pi^2 / 2L) \Sigma d \times 100$$

where SA = surface area (m^2/ha)
L = length of transect line (m)
d = piece diameter (cm)

LWD surface area was calculated using the formula for the surface area of a cylinder;

$$SA_{piece} = \Pi \times d \times l \times 100$$

where SA_{piece} = surface area (m^2)
l = length of piece (m)
d = diameter (cm)

LWD surface area (m^2/ha) was calculated using the same procedure as for LWD volume.

A two-sample t-test was used to determine whether there were differences in the size and length and piece size of the LWD pieces at pre-harvest and harvest. To analyse the effect of the harvesting systems and practices used on the harvest woody debris characteristics, analysis of variance (ANOVA) and least significant difference (LSD) tests were used to determine whether there were any relationships between the four harvesting methods and harvest total woody debris volumes, log transformation of harvest total woody debris volumes, SWD volumes, LWD volumes, position of woody debris in the stream channel, stand volume, and ground slope.

Channel bank disturbances were expressed as a percentage of channel bank length disturbed. As both sides of the 100-m section of channel bank were assessed, total channel bank length was 200 m. A paired t-test was used to determine differences in the amount of channel bank disturbance before harvest and any additional disturbance after harvest. A one-way ANOVA was used to determine whether the harvesting methods affected the percentage of channel bank disturbed.

RESULTS

Woody Debris Characteristics

Woody debris volumes and surface areas before and after harvesting for each site are listed in Appendix 1 and summarised in Table 4. Pre-harvest woody debris is defined as the woody debris in the stream channel prior to harvest, and harvest woody debris as the additional woody debris added to the stream channel from the harvest operation. The pre-

TABLE 4—Summary of pre-harvest, harvest, and post-harvest woody debris volumes and surface areas in the stream channel by harvest method (± 95% confidence interval).

	Pre-harvest		Harvest		Post-harvest		Increase on pre-harvest	
	Volume (m^3/ha)	Surface area (m^2/ha)	Volume (m^3/ha)	Surface area (m^2/ha)	Volume (m^3/ha)	Surface area (m^2/ha)	Volumes (%)	Surface area (%)
Method 1—stream-cleaned (n = 3)								
Mean	67	1916	15*a*	1 427	*	*	*	*
Method 2—ground-based (n = 5)								
Mean	169	3630	48*a*	3 866	218	7 496	20	78
Method 3—haul back from stream edge (n = 2)								
Mean	87	3155	104*ab*	8 492	191	11 646	127	246
Method 4—haul across stream channel (n = 7)								
Mean	81	2166	287*b*†	20 657†	368	22 823	617	1226
Total Mean	105 ± 42	2669 ± 839	147 ± 84	10 894 ± 5828	289 ± 100	15 753 ± 6631	334	676

* These sites were stream-cleaned removing most of the pre-harvest and harvest material so pre harvest + harvest volumes and surface areas do not equal post-harvest volumes and surface areas.

† Volumes and surface areas under-estimated in three sites, unable to reach all the harvest woody debris in the stream channel.

Harvest volumes followed by different letters are significantly different ($p < 0.05$).

harvest and harvest woody debris volumes and surface areas were added together to give post-harvest woody debris volumes and surface areas (excluding Method 1). It was not possible to do this for Method 1 as these sites were stream-cleaned, removing most of the woody debris from the stream channel.

Pre-harvest woody debris volumes averaged 105 ± 42 m^3/ha (95% CI) and ranged from 2 to 345 m^3/ha. Harvesting contributed on average an additional 147 ± 84 m^3/ha of woody debris to the stream channel, ranging from 2 to 528 m^3/ha. At the four sites that had native riparian buffers, riparian buffer vegetation displaced into the stream during felling and log extraction made up 29%, 51%, 58%, and 35%, respectively, of the harvest volumes. Post-harvest woody debris volumes averaged 289 ± 100 m^3/ha (excluding Method 1), and ranged from 66 to 596 m^3/ha.

Woody debris surface areas averaged 2669 ± 839 m^2/ha at pre-harvest and 10 894 ± 5828 m^2/ha at harvest (Table 4), while post-harvest woody debris surface areas averaged 15 753 ± 6631 m^2/ha (excluding Method 1).

Most of the woody debris at pre-harvest, woody debris produced during harvesting, and total post-harvest woody debris, was positioned above the stream—69%, 64%, and 66% respectively (Fig. 2). At two sites, the proportions of harvest woody debris volumes in the above stream and floodplain categories have been estimated using the channel morphology measurements as the amount of woody debris in the stream channel made it difficult to determine this boundary in the field. Woody debris surface areas showed a similar trend to woody debris volumes with most of the surface area above the stream (64% at pre-harvest, 72% in woody debris from harvest, and 72% in total post-harvest woody debris).

The proportions of SWD and LWD in the stream channel changed between pre- and post-harvest (Table 5). At pre-harvest 13% of woody debris volumes was composed of SWD. This increased to 38% at post-harvest. SWD surface areas showed a similar increase (from 50% to 82%). This pattern was also reflected in the pre-harvest and harvest diameter distributions

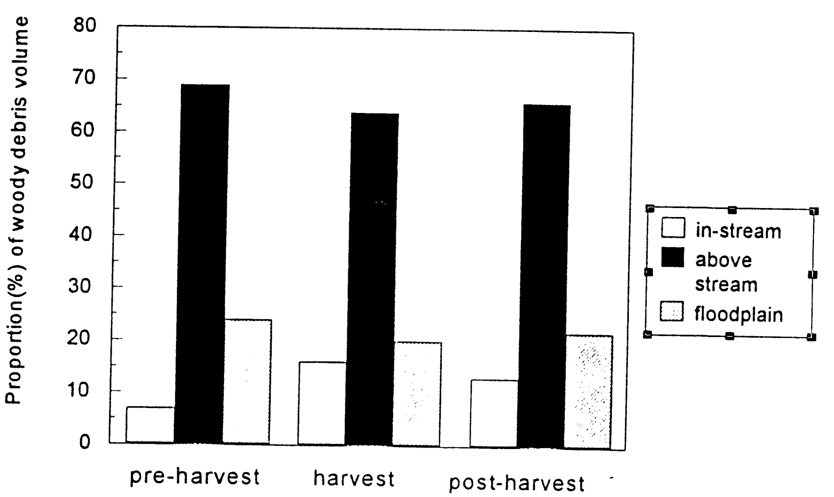

FIG. 2–Position of woody debris volume in the stream channel, pre-harvest, at harvest, and post-harvest (average of the 17 sites).

TABLE 5–Composition of pre-harvest, harvest, and post-harvest woody debris volume and surface area (average of the 17 sites).

	Woody debris volume		Woody debris surface area	
	SWD %	LWD %	SWD %	LWD %
Pre-harvest	13	87	50	50
Harvest	55	45	89	11
Post-harvest	38	62	82	18

(Fig. 3). Pre-harvest woody debris was normally distributed by volume across the diameter classes, whereas woody debris volumes produced during harvest were skewed toward the smaller diameter classes.

Prior to harvest, 354 pieces of LWD were measured across all sites. Harvesting operations left an additional 552 pieces of LWD in the stream channel, a 56% increase on pre-harvest numbers. LWD diameters were similar for both pre-harvest and harvest woody debris, averaging 22 cm and 21 cm, respectively. The average length of the LWD pieces from harvesting (1.8 m) was significantly shorter than at pre-harvest (3.2 m) ($p = 0.005$). This was reflected in the average volume of the LWD pieces. LWD pieces from harvest (0.05 m^3) were significantly smaller ($p = 0.0008$) than pre-harvest LWD pieces (0.17 m^3).

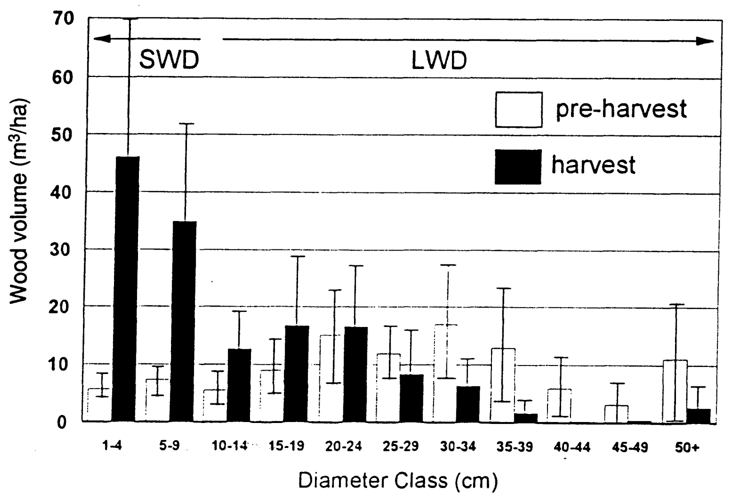

FIG 3–Distribution of pre-harvest and harvest wood volumes by diameter class (average of the 17 sites). All diameter classes are in 5-cm class intervals except for the lowest and highest diameter classes. Error bars are the 95% CI for each diameter class. Error bars were too small to record on the graph for the harvest diameter classes 40–44 cm and 45–49 cm.

Harvesting Method

Method 1 had the lowest harvest woody debris volumes produced during harvesting, followed by Methods 2, 3, and 4 (Table 4). The harvest volumes in Methods 1, 2, and 3 did not differ significantly from each other, but harvest volumes in Methods 1 and 2 were significantly lower than the harvest volumes in Method 4 ($p < 0.05$) (Table 4). Harvest volumes in Method 3 were also lower than in Method 4, but the difference was not significant ($p = 0.07$).

Except for Method 1 stream-clean, there was no relationship between the harvesting method and the volume and position of the SWD and LWD in the stream channel. Harvest wood volumes above stream were significantly lower for Method 1 than for the other three methods ($p < 0.05$).

Ground slope and stand volume did not appear to influence harvest volumes in Methods 1, 2, and 3. In Method 4, there was a relationship between stand volume and harvest woody debris volume which is expressed in the equation:

$\log_e$ (harvest woody debris volume) = 1.57 + 0.0015 stand volume ($R^2 = 0.67$, $p=0.02$)

Channel Bank Disturbance

The types and amounts of channel bank disturbances recorded at pre- and post-harvest are outlined in Tables 6 and 7. Only visible channel bank disturbances were recorded at Sites 14 and 17 as harvesting woody debris obscured some of the stream channel. Disturbances may have been under-estimated for these sites.

TABLE 6–Amount of channel bank disturbance, pre- and post-harvest

Site	Channel bank disturbances (%)*			Soil loss (m^3)	
	Pre-harvest	Post-harvest†	Post-harvest† scuffs and ruts only	Pre-harvest	Post-harvest†
Method 1—stream-cleaned					
1	36	0	0	4	0
2	1	6	5	2	5
3	6	2	0	0	2
Method 2—ground-based					
8	0	1	1	0	1
9	0	1	0	0	0
10	0	0	0	0	0
12	3	3	3	1	0
16	0	2	1	0	0
Method 3—haul back from stream edge					
5	16	2	1	9	1
7	0	4	0	0	1
Method 4—haul across stream channel					
4	0	39	37	0	44
6	0	19	5	0	7
11	5	13	13	33	1
13	5	1	0	22	1
14	0	1	1	0	0
15	8	6	6	18	4
17	0	9	3	0	15
Total Mean	5	6	4	5	5

* Length of channel bank disturbed expressed as a percentage of the total channel bank length (200 m, both sides of the stream channel)

† Additional channel bank disturbances and soil loss since pre-harvest assessment

TABLE 7–Types of channel bank disturbance, pre- and post-harvest (average of the 17 sites)

	Pre-harvest		Post-harvest	
	Percentage	Percentage soil loss	Percentage	Percentage soil loss
Bank collapse	68	83	25	35
Bank slump	13	–	21	–
Lateral scour	18	17	–	–
Direct harvest disturbance				
Bank scuff	–	–	46	63
Rut	–	–	7	2

Due to rounding conventions, percentage totals do not all equal 100%

Prior to harvest, nine of the 17 sites had no fresh channel bank disturbances (Table 6). At the other sites, length of channel bank disturbed varied from 1% to 36% but was mostly less than 10%. Sites 1 and 5 had the highest amounts of disturbance (36% and 16%), due in part to disturbance from floods during two cyclones, one in December 1996 and the other in January 1997. Seven sites recorded channel bank disturbances that had resulted in soil loss ranging from 1 to 33 m^3. Bank collapses accounted for 68% of all pre-harvest disturbances (Table 7) and 83% of the soil lost. The remaining soil was lost to lateral scouring of the stream channel.

After harvest, there were two sites with no additional channel bank disturbance (Sites 1 and 10). At the other sites, the length of channel bank disturbance varied from 1% to 39% (Table 6). Bank scuffing from felling and log extraction was the most common type of channel bank disturbance (46%) accounting for 63% of the soil lost (Table 7). The rest was lost from bank collapses and ruts.

Harvest method did not appear to affect the amount of channel bank disturbance ($p > 0.05$). This was also true when harvest method was compared with only the channel bank disturbances attributable directly to harvest (bank scuffs and ruts) (Table 6).

DISCUSSION

Harvest Methods and Woody Debris Characteristics

Most of the harvesting operations in this study increased woody debris volumes, by an average of three-fold over pre-harvest levels. Collier, Bowman, & Halliday (unpubl. data) measured a similar increase in three central North Island streams after harvest. In one North American study (Froehlich 1977), only sites harvested by conventional yarder operations showed a similar increase in woody debris volumes after harvest. Otherwise, post-harvest woody debris levels were similar to, or less than, pre-harvest levels (Froehlich 1977; Toews & Moore 1982a). This was because merchantable pre-harvest woody debris was removed at harvest, or directional felling, extraction techniques, and riparian buffers limited the amount of harvest woody debris reaching the stream channel. In New Zealand's pine plantations wood from the main tree species, *P. radiata*, is susceptible to fungal attack and deteriorates quickly (Riddle 1996) so that, unlike North America, there is little or no merchantable timber in the stream channel prior to harvest. With the exception of the stream-cleaned sites, this material is left in the stream channel at harvest.

Similar to the North American studies, the directional felling and extraction techniques in Methods 2 and 3 also limited the amounts of harvest woody debris reaching the stream channel. However, the influence of riparian buffers on woody debris volumes in the stream was not so obvious in our study. In contrast, both Froehlich (1977) and Toews & Moore (1982a) found that riparian buffers reduced the amount of woody debris reaching the channel system during harvesting. In our study, the harvest method used influenced harvest woody debris volumes more than the presence or absence of a riparian buffer. At Sites 5 and 16, where harvest volumes were low, the felling and extraction direction was away from the riparian buffer (Methods 3 and 2 respectively). The slightly higher volumes at Site 13, were a result of extracting the timber through two corridors in the riparian buffer. At Site 4, which had the highest harvest volumes, timber was extracted across the riparian buffer (Method 4). The sample size was too small to statistically test the differences between methods.

Harvesting increased the proportion of SWD in the stream channel regardless of the method used, increased the number of LWD pieces, and decreased the average length and volume of LWD pieces, a trend similar to overseas studies (Froehlich 1977; Toews & Moore 1982a; Sedell *et al.* 1988). This was due to smaller material such as branches and broken tops falling or being swept into the stream channel during harvesting operations. It also reflects the prescription requirements to fell and extract trees away from the stream edge and to remove the larger merchantable pieces of timber from the stream channel.

The smaller, shorter pieces of wood left in the channel after harvest are likely to be unstable and more mobile than pre-harvest woody debris during high flows. Both Harmon *et al.* (1986) and Sedell *et al.* (1988) found piece size and length of woody debris were two important factors affecting the stability of woody debris in the stream channel. Toews & Moore (1982a) recorded a reduction in the LWD stability indices after harvest and they attributed this to smaller, more mobile material left in the stream channel. This material accumulated into dams, changing the characteristics of the channel morphology and increasing stream bank erosion. Similar results were recorded by Hogan (1987) and Sedell *et al.* (1988). As SWD volumes increased significantly and LWD length and piece size decreased significantly after harvesting in this study, it is likely that this material will be less stable and more mobile than the pre-harvest woody debris.

The changes in amount and size distribution of woody debris in the stream channel after harvesting are likely to affect the channel morphology of the stream. In overseas studies, stream-cleaning after harvest reduced the ability of the stream channel to store sediment, decreased channel stability, and reduced the number of pools in the stream channel (Sedell *et al.* 1988; Commandeur *et al.* 1996). Some retention of woody debris from harvesting (especially the LWD) can contribute to reducing stream velocity and providing storage locations for sediment. In a North American study, where logging slash was left in the channel, 66% of the sediment inputs into the stream were stored in the channel. In the channel where logging slash was removed, 37% of the sediment input was stored in the channel (Commandeur *et al.* 1996).

Changes in woody debris volumes in the stream channel after harvest can affect water quality and stream biota. High levels of woody debris from harvest can lower dissolved oxygen (DO) levels in the central North Island streams of New Zealand (Pruden & Coker unpubl. data; Collier, Bowman, & Halliday (unpubl. data), indicating that high organic loading can increase the oxygen demand in the stream. DO levels in the cool spring-fed streams at these central North Island sites ranged from 60% to 75% saturation compared with 90–100% saturation in native and unharvested sites, and in sites where varying levels of harvest woody debris had been removed from the stream channel. However, the post-harvest in-stream (submerged) wood volumes in Collier, Bowman, & Halliday (unpubl. data) study were much higher (> 200 m^3/ha) than the in-stream volumes in this study which averaged 37 m^3/ha.

Retaining some woody debris can be beneficial for temperature control, particularly when sufficient woody debris from harvest remains suspended above the stream channel. Its moderating effect is most beneficial during the summer months (Collier *et al.* 1997). Most of the woody debris volumes in this study were suspended above the stream channel (Fig. 1). Stream-cleaning can raise temperatures to levels considered stressful to sensitive aquatic life, if these temperatures are maintained for long periods (Quinn *et al.* 1994; Collier *et al.* 1997). Woody debris from harvesting can also affect aquatic invertebrate density, which declined in one study where all the woody debris was left in the stream channel (Collier, Bowman, & Halliday unpubl. data) and also declined in another study where varying levels of woody debris were left in the stream channel (Pruden & Coker unpubl. data).

In areas of high episodic rainfall and frequent flood events, possible ecological benefits of leaving some woody debris in the stream channel have to be balanced against the risk of debris dams moving down stream and adversely affecting down-stream infrastructures and stream habitat.

Long-term implications of post-harvest woody debris in the stream channel also need to be considered. Most of the woody debris in this study was suspended above the stream and will break down over time, falling into the water column. The LWD component has been shown to last in stable streams for more than 20 years and can be beneficial to aquatic invertebrates in streams with mobile bed substrates (Collier, Bowman, & Halliday unpubl. data).

Harvest Methods and Channel Bank Disturbance

Although harvesting accounted for most of the post-harvest channel bank disturbance and soil loss (Tables 6 and 7), there was little difference between the harvesting method used and the degree of channel bank disturbance recorded. It was expected that channel bank disturbance would be highest for Method 4 where trees were extracted across the stream channel and lowest for Methods 2 and 3 where extraction direction was back from the stream edge, but this proved not to be true. This contrasts with the findings of Toews & Moore (1982b) who found differences in channel bank disturbance depending on the harvest method used. They recorded very little immediate channel bank disturbance after harvesting in the "careful" treatment site but numerous instances of disturbance in the "intense" treatment site. It is possible that the partial suspension of logs across the stream channel, and buffering from vegetation, may have been reasons for the lower than expected levels of channel bank disturbance in Method 4.

CONCLUSION

The range of harvesting systems and practices used to harvest along stream edges has resulted in varying amounts of woody debris in the stream channel. This woody debris is more abundant and smaller than pre-harvest woody debris and is likely to be more unstable. As a consequence the effect on the stream ecosystem is also likely to be varied and complex, depending not only on the amount, size, and distribution of the woody debris in the stream channel, but also on other factors such as climate, and the hydrological and geological characteristics of the stream channel. The short-term consequences of woody debris from harvest need to balanced against risk factors to down-stream infrastructures and habitats and long-term influences on the stream ecosystem.

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APPENDIX 1

PRE- AND POST-HARVEST WOODY DEBRIS VOLUMES AND SURFACE AREAS IN THE STREAM CHANNEL

Site/ Harvest method*	Pre-harvest volume (m^3/ha)	Harvest volume (m^3/ha)	Post-harvest volume (m^3/ha)	Increase on pre-harvest volume (%)	Pre-harvest surface area (m^2/ha)	Harvest surface area (m^2/ha)	Post-harvest surface area (m^2/ha)	Increase on pre-harvest surface area (%)
1/1	145	38	†	†	4393	3 321	†	†
2/1	2	6	†	†	220	667	†	†
3/1	54	2	†	†	1136	292	†	†
4/4	53	344	397	651	2045	19 924	21 969	974
5/3	28	38	66	138	1540	3109	4 649	202
6/4	68	528	596	781	1614	39 764	41 378	2464
7/3	145	167‡	312‡	115‡	4770	13 874‡	18 644‡	291‡
8/2	144	22	167	15	3322	1 829	5 151	55
9/2	97	13	111	14	3065	688	3 753	22
10/2	108	9	117	8	2638	344	2 982	13
11/4	10	147	157	1457	623	14 594	15 217	2342
12/2	345	177	522	51	6769	14 508	21 276	214
13/4	182	86	269	47	3163	6 442	9 605	204
14/4	40	356‡	396‡	899‡	2388	211 137‡	23 525‡	885‡
15/4	75	154	229	206	1643	16 414	18 057	999
16/2	152	20	172	13	2358	1 962	4 320	83
17/4	140	391‡	531‡	279‡	3691	26 320‡	30 011‡	713‡

* Harvest method: 1 = stream-cleaned; 2 = ground-based; 3 = haul back from stream edge; 4 = haul across stream channel

† These sites were stream-cleaned, removing most of the pre-harvest and harvest material, and so pre-harvest + harvest volumes and surface areas do not equal post-harvest volumes and surface areas.

‡ Volumes and surface areas under-estimated in three sites, as assessors were unable to reach all the harvest woody debris in the stream channel.