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TIMBER HARVEST IMPACTS ON SMALL HEADWATER STREAM CHANNELS IN THE COAST RANGES OF WASHINGTON[1]

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ABSTRACT: We evaluated changes in channel habitat distributions, particle-size distributions of bed material, and stream temperatures in a total of 15 first- or second-order streams within and nearby four planned commercial timber harvest units prior to and following timber harvest. Four of the 15 stream basins were not harvested, and these streams served as references. Three streams were cut with unthinned riparian buffers; one was cut with a partial buffer; one was cut with a buffer of non-merchantable trees; and the remaining six basins were clearcut to the channel edge. In the clearcut streams, logging debris covered or buried 98 percent of the channel length to an average depth of 0.94 meters. The slash trapped fine sediment in the channel by inhibiting fluvial transport, and the average percentage of fines increased from 12 percent to 44 percent. The trees along buffered streams served as a fence to keep out logging debris during the first summer following timber harvest. Particle size distributions and habitat distributions in the buffered and reference streams were largely unchanged from the pre-harvest to post-harvest surveys. The debris that buried the clearcut streams effectively shaded most of these streams and protected them from temperature increases. These surveys have documented immediate channel changes due to timber harvest, but channel conditions will evolve over time as the slash decays and becomes redistributed and as new vegetation develops on the channel margins.

(KEY TERMS: aquatic ecosystems; nonpoint source pollution; sedimentation; channel morphology; stream habitat; riparian vegetation.)

INTRODUCTION

The benefits of forested buffers on fish-bearing streams are well known, and most research efforts now focus on the appropriate width and stocking of buffers rather than on whether buffers are needed. Small headwater streams in the Pacific Northwest, however, often do not support fish, and therefore the necessity of buffers is a subject of debate. In Washington and Oregon, rules for forest practices have not traditionally required buffers on nonfish-bearing headwater streams. Since first- and second-order stream density in the Washington Coast Ranges is in the range of 7 kilometers/square kilometer, the economic cost of buffers on all such streams is large. Because land managers focus on fish habitat, little descriptive information on either natural channel conditions in first- and second-order nonfish-bearing streams or on the response of these streams to timber management exists. Previous Pacific Northwest stream studies (e.g., Bilby and Ward, 1989; Montgomery *et al.*, 1995) have looked at streams greater than four meters in width. Basic information on timber harvest impacts on the morphology, temperature, and biotic communities of first- and second-order streams with channel widths in the range of one to three meters is scarce.

We studied a sample of headwater Coast Range streams to describe what happens to these streams when the timber is harvested from their catchments. This is part of a larger study that also considers the amphibian and macroinvertebrate communities in these streams. Specifically, we surveyed physical channel features and amphibian and invertebrate communities before and after timber harvest in 15 first- and second-order streams within and adjacent to four commercial logging sites. Trees were harvested by clearcutting. The trees were felled with chainsaws and yarded by high-lead cable yarding. Sites were harvested by commercial loggers using techniques

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standard to the industry. This paper describes observed changes in channel habitat, particle size distributions, woody debris, and water temperatures. Biotic conditions and changes in these channels will be described in other papers.

LITERATURE REVIEW

Expectations of the effects of timber harvest on adjacent channels are guided by the stream continuum concept (Vannote *et al.,* 1980) and by the application of energy budget principles (Brown, 1970). After removal of the canopy cover from adjacent forests, solar insolation of the stream should increase as should sensible heat exchange due to the loss of the wind screen. As observed in many previous studies, the increased energy input results in higher daily average and maximum stream temperatures during the summer (Greene, 1950; Brown and Krygier, 1967, 1970; Hewlett and Fortson, 1982; Beschta and Taylor, 1988). The increased solar insolation also should stimulate primary productivity in the stream (Noel *et al.,* 1986; Wallace and Gurtz, 1986; Feminella *et al.,* 1989; Stone and Wallace, 1998) resulting in higher algal production, a shift of the macroinvertebrate community from shredders to grazers, and a potential increase in available food for fish (e.g., Hetrick *et al.,* 1998). The loss of canopy cover should decrease allocthonous (i.e. originating outside the channel) organic input to the stream, also driving a shift of the macroinvertebrate community from shredders to grazers (e.g., O'Hop *et al.,* 1984; Wallace *et al.,* 1997). Studies have documented reduced large woody debris frequency and size in managed streams due to the reduction of large woody debris recruitment potential following harvest (Bilby and Ward, 1991; Bilby and Wasserman, 1989; Ralph *et al.,* 1994). Reductions in large woody debris (LWD) result in a reduction of steps, obstructions, and pools or essentially a simplification of channel habitat (Hicks *et al.,* 1991; Fausch and Northcote, 1992).

In a cross-landscape comparison of logged and unlogged streams in western Oregon, Corn and Bury (1989) found fewer *Dicamptodon tenebrosus* (Pacific Giant Salamanders) in logged streams. A finer particle size distribution in the logged streams was the only physical difference found in the streams. They hypothesized the higher sediment loads in the logged streams reduced habitat for Dicamptodon by filling in the interstitial crevices they prefer (Hall *et al.,* 1978; Murphy and Hall, 1981).

Because ground water discharge dominates as the source of flow, small headwater streams in the Pacific Northwest tend to have very cold water temperatures, and many researchers have suggested that these cold temperatures are a requirement for stream-dwelling amphibians. Welsh and Lind (1992) found *Rhyacotriton variegatus* (southern torrent salamander) in streams ranging in temperature from 6.5 to 14.5°C and found maximum densities in streams with temperatures around 11°C. These temperature measurements were not controlled for time of day or time of year. The temperature relations of *Ascaphus truei* (tailed frog) have been studied extensively. Bury (1968) reported that temperatures in streams inhabited by *A. truei* range from 2°C to 15.5°C, and Noble and Putnam (1931) found no *A. truei* in streams above 16°C. In laboratory tests, DeVlaming and Bury (1970) found that first-year tailed frog tadpoles preferred temperatures less than 10°C, second year tadpoles preferred temperatures between 10 and 16°C, and all tadpoles avoided temperatures above 22°C. Brown (1975) evaluated the development of tailed frog eggs and found the temperature range for normal egg development was 7.6 to 18.0°C. Alternatively, Metter (1966) and Metter and Pauken (1969) suggested that relative humidity was a more important habitat factor than temperature and that *A. truei* could survive at 20°C if relative humidity was high. Numerous researchers have inferred from cross-landscape comparisons that *A. truei* are very sensitive to timber harvest and are often eliminated from streams by adjacent timber harvest. Both the requirements for coarse substrate and cold water temperatures have been cited as the reasons for sensitivity to timber harvest.

The harvest impacts observed in this set of study streams are different from those observed in the literature discussed above. The logging operations left our streams covered or buried with logging debris which completely altered the expected shifts in physical and biological channel conditions. Differences in landscape setting and differences in study design are the primary reasons. All of the streams in this study have channel widths less than four meters and basin areas between 0.011 and 0.081 square kilometers, while the streams in previous studies have been larger or have used different harvest methods. Also, most of the studies addressing logging impacts are cross-landscape comparisons where the harvests occurred many years earlier. Studies comparing pre- and post-harvest channel conditions in the same channels are rare. In the few studies that have looked at immediate impacts of timber harvest on small streams (Froehlich, 1973; Kelsey, 1995), large amounts of woody debris from logging slash also were observed in the streams following harvest.

STUDY SITES

All of the study sites are in located in the Coast Ranges of western Washington within 60 miles of the Pacific Ocean, and all of the sites are within commercial timber land owned by Rayonier. Site 21 is located in the southern foothills of the Olympic Mountains; Site 17 is on the south shore of Grays Harbor; and Sites 12 and 13 are within the Willapa Hills of southwest Washington. Table 1 summarizes basic site characteristics.

Site selection for this project was a difficult and iterative process. Originally, it was our goal to find planned logging units with four nonfish-bearing perennial headwater streams and a nearby reference stream so that the effects of a clearcut and three alternative riparian treatments could be evaluated. Furthermore, logging had to be scheduled between August 1998 and June 1999 so that pre-harvest data could be collected in the summer of 1998 and post-harvest data could be collected in the summer of 1999. Most modern clearcut units, however, are not large enough to contain four perennial headwater streams. Therefore, the criterion for the number of in-unit streams was reduced to three. At least three suitable sites were needed for replication of treatment effects. Each site was supposed to contain four streams which were to receive the following treatments: no adjacent harvest (reference stream), standard clearcut, full riparian buffer, and a non-merchantable tree buffer. In actuality, non-merchantable trees were rare because overstory timber was uniformly mature conifers, so most of the non-merchantable buffer streams effectively became clearcuts. An effective non-merchantable treatment was applied to only one stream on only one site. Also, one of the streams on site 12 went dry and was not used in the study. The distribution of treatment types is summarized in Table 1.

All of streams except two were unaffected by road crossings or road runoffs. Stream 21M was impacted by road and log landing runoff in the second year of sampling. The reference stream on Site 13 (13R) also had a logging road crossing. On all other streams, logging roads were located well upslope of the channel heads, and there were no surface flow paths between the roads and the streams. Therefore, the harvest effects observed in this study cannot be attributed to logging roads. Widths of buffers applied to the buffered streams were dictated by operational considerations, and the average total buffer width varied from 15 to 21 meters. The shortest width measured on one side of a buffered stream was 2.3 meters.

TABLE 1. Description of Riparian Treatment Sites.

	Unit 13.191	Unit 12.129	Unit 17.039	Unit 21.329
General Location	Willapa Hills; Palix River Basin	Willapa Hills; Willapa River Basin	South shore of Grays Harbor; Newskah Creek Basin	Southwestern Olympic foothills; Humptulips River Basin
Legal Location, Willamette Meridian	T13NR09W, sec 20	T12NR08W, sec 08	T17NR09W, sec 28	T21NR09W, sec 07
Geology	Basalt	Basalt	Mixed marine sediments and glacial outwash	Marine basalt with glacial outwash overlay
Topography *(typical side slopes and channel gradients)*	Steep slopes (average 33°) Moderate channels (average 15 percent)	Very steep slopes (average 41°) Steep channels (average 29 percent)	Steel slopes (average 32°) Moderate channels (average 19 percent)	Low slopes (average 12°) Moderate channels (average 11 percent)
Elevation (meters)	108-258	345-615	37-165	198-385
	Number of Study Streams in (or nearby) Logging Unit (by treatment type)			
Reference	1	1	1	1
Clearcut	2	1.5*	2	1
Full Buffer	1	0.5*	1	1
Nonmerchantable Buffer	–	–	–	1

*One-half of the survey section of one of the clearcut streams fell within the buffer of the fish-bearing stream below.

METHODS

Channel surveys were conducted to provide physical data for habitat models and to provide a baseline from which to measure channel changes after treatment. The surveys collected physical information equivalent to that measured by Wilkins and Peterson (2000) and by Corn and Bury (1989) as well as additional information. The surveys were conducted from the base of the amphibian survey reach and extend upstream approximately 20 channel widths, or to the end of the channel, or to an obvious break in overall channel morphology. The first-order streams in our study areas are quite short. In some cases, the total length of stream is less than 100 meters. We measured the length, width, and height or drop of each channel habitat unit. The common channel habitat units included riffles, pools, steps, subsurface flow, bedrock cascades, and runs. We counted LWD as functional (defined as creating pools, trapping sediments, forming jams, protecting banks, or altering flow hydraulics) and nonfunctional (not altering flow hydraulics). Particle size distributions were quantified using three methodologies: Wolman pebble counts (three riffles), zig-zag pebble counts (N = 200), and substrate samples collected in three randomly-selected locations and composited. For each step or jam, we identified the forming agent (cobble, wood, boulder, etc.), and we measured and counted the wood that helps form each jam. At the end of each survey, we measured the total elevation drop over the surveyed channel. Prior to conducting the channel survey, basic site data was collected on canopy closure, overstory and understory characteristics, weather, light levels, and location. Two valley profiles were surveyed to characterize the side slopes and the valley morphology.

Temperatures were measured using HOBO® XT temperature loggers which were programmed to collect temperatures on an hourly basis. The loggers were placed in waterproof cases with temperature sensors attached to the inside wall of the case. The cases were set in the bottom of the streams, usually in five to ten centimeters of water, with rocks placed on top of the cases to prevent them being washed away in freshets. During both the pre- and post-harvest summers, the temperature loggers were placed in the streams in early to mid-June and were removed in early to mid-August.

The pre-harvest channel surveys were conducted during the summer of 1998. The sites were all logged in the spring or early summer of 1999. The process of logging and yarding each site generally spanned about two months. The channel surveys usually followed the completion of logging and yarding by about a month. For these reasons, the post-harvest results of this project portray channel conditions immediately after harvest. These conditions are likely to change rapidly over the next few years as the logging debris decays or is mobilized during high flows or as windstorms blow over trees in the buffer.

RESULTS

Channel Morphology

In their pre-harvest conditions, most of these streams featured step-riffle morphology. Riffles accounted for 64 percent of channel length, and steps accounted for 15 percent of channel length and 43 percent of channel elevation drop. While the streams featured a relatively high frequency of steps, plunge pools were rare because these small streams lack sufficient fluvial power to carve pools. Therefore, these streams do not fit into the Montgomery-Buffington classification system for mountain streams (Montgomery and Buffington, 1997). The cumulative distribution of habitat types over all pre-harvest streams is illustrated in Figure 1.

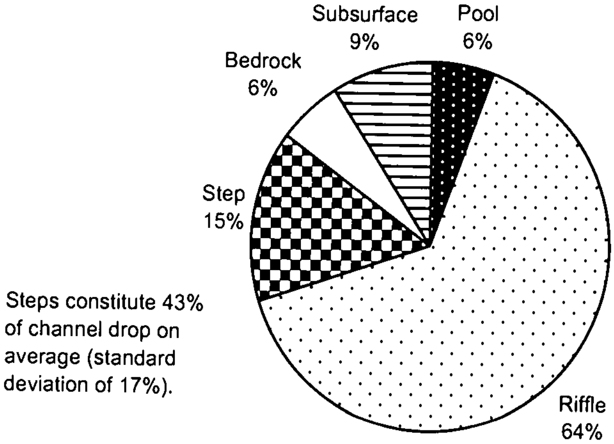

Figure 1. Cumulative Distribution of Habitat Based on Longitudinal Channel Distance in the 15 Study Streams Prior to Harvest.

Logging without buffers had immediate and dramatic effects on channel morphology. In the relatively steep topography of the study sites, logging debris tended to accumulate at the bottom of slopes and thereby bury the headwater streams that lacked riparian buffers. During logging, the cutters drop the tops of the trees downslope, and thus the stream valleys are covered by the tops of trees cut from both sides of the valleys. The tops and the branches are removed prior to yarding of the logs, and these tops and branches remain where they fall, which is on top of the streams. Consequently, the dramatic morphological effect of clearcutting across headwater streams was the covering or burial of streams with 0.5 meter to 2.0 meters of organic debris (average 0.94 meters). This organic debris consisted of whole branches including needles, small twigs, and logs.

In the post-harvest surveys, we developed two new channel habitat classifications: covered and buried. In a covered channel, flow is completely obscured by organic debris, but a recognizable channel still exists below the debris. This channel cannot be surveyed by humans, however. A buried channel has so much organic detritus in the flow cross-section that the channel is no longer definable. Instead, the water flows through a porous medium composed of organic debris and soil which completely fills the former channel cross-section. As shown in Table 2, a total of about 94 percent of the linear length of the clearcut streams was either covered or buried. Lumping all streams together, about 48 percent of the channel length was buried and about 46 percent was covered, but the distribution of buried and covered channels varied greatly between streams. Approximately one-third of the survey length of one of the clearcut streams was in the buffer of a second-order fish-bearing stream, and this section of this channel was protected from burial. If this section is removed from the data, the sum of buried and covered channel increases to 98 percent of the clearcut channel length.

The buffered streams were protected from burial or coverage because the trees left in the buffer act as a fence to keep out the organic debris. As shown in Table 2, almost none of the buffered stream length was covered or buried by organic debris. The exception was one stream where a wind storm had blown down some of the trees in the buffer leaving them to span the channel. These blown-down trees did not significantly alter the underlying channel morphology. Visual reconnaissance also indicated that the buffers maintained bank stability in the channels. Figure 2 illustrates the distribution of habitat types in the buffered streams before and after harvest. Post-harvest surveys found the same amount of step habitat in the buffered streams, but also found an increase in the amount of pool habitat and a decrease in the amount of subsurface habitat. It is not known whether these changes reflect temporal variability in

TABLE 2. Burial and Coverage of Streams by Slash After Harvest.

Stream	Percent Buried	Burial Depth (m)	Percent Covered	Cover Depth (m)	Sum of Buried and (percent)	Survey Length (m)	Length Buried (m)	Length Covered (m)
				CLEARCUT STREAMS				
12E*	44	1.8	28	2.3	72	27.7	12.3	7.7
12W	6	1.0	91	0.9	97	27.0	1.5	24.5
17W	64	1.0	36	1.0	100	21.0	13.4	7.6
17M	42	1.6	58	1.4	100	23.0	9.6	13.4
21E	7	0.5	85	0.6	92	27.6	2.0	23.4
13S	90	0.6	8	0.2	98	50.0	44.9	4.2
13M	52	1.0	48	0.4	100	35.0	18.3	16.7
				Weighted Averaged for Clearcut Streams				
	48	0.97	46	0.90	94	211.3	102.0	97.5
				BUFFERED STREAMS				
17E**	0	–	29	(blowdown)	29	28.3	–	8.3
21M	0	–	0	–	0	35.0	–	–
13E	0	–	0	–	0	25.0	–	–
21W***	0	–	–	–	0	27.3	–	–

*Lower portion of surveyed section of 12E was within the buffer of fish-bearing stream.
**Stream 17E partially covered by blowdown trees from buffer.
***Stream 21W features the only nonmerchantable buffer in the study.

habitat, possibly due to a high number of scour events in the winter of 1998 to 1999, or if they are an artifact of a relatively small sample size (four streams and a total of 116 meters of channel), or if they reflect a drift toward greater habitat resolution by the survey team. Most of the loss of subsurface habitat and gain in bedrock habitat was due to partial buffer blowdown on one of the streams where the fallen trees caused some channel disturbance. Similarly, a single buffered channel accounted for most of the increase in pool habitat. As a point of comparison, Figure 3 illustrates the 1998 and 1999 habitat distributions in the reference streams. There is almost no change in the habitat distributions in the reference streams.

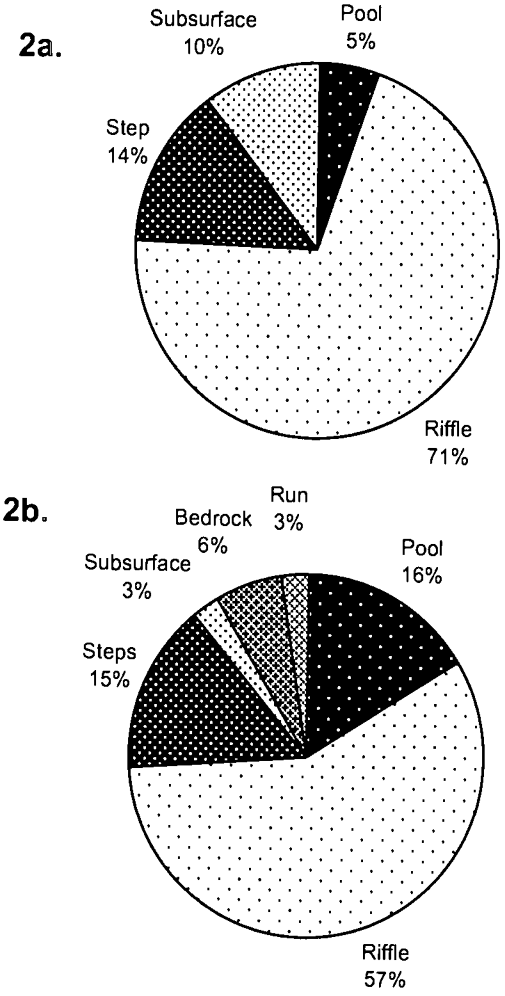

Figure 2. Comparison of (1) Pre-Harvest and (b) Post-Harvest Habitat Distributions in the Three Fully-Buffered Streams and the One Stream Buffered With Nonmerchantable Trees. Relative habitat distribution is based on longitudinal channel distance.

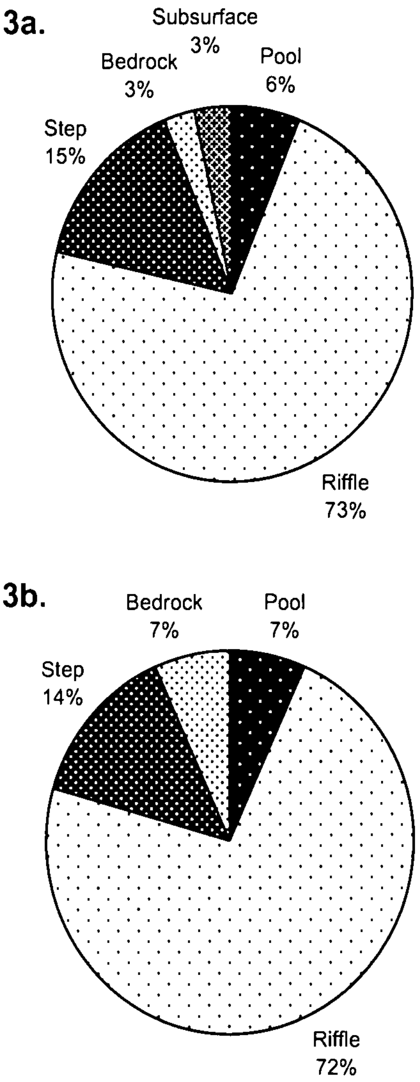

Figure 3. Comparison of (a) Pre-Harvest and (b) Post-Harvest Habitat Distributions in the Four Reference Streams Based on Longitudinal Channel Distance.

Particle Size Distributions

The coverage and burial of the channel made it impossible to redo the zig-zag or standard Wolman pebble counts. Therefore, pre- and post-harvest sediment size distributions were compared using sieved grab samples from the bed. In the pre-harvest surveys, three grab samples were taken at randomly selected places, and these locations were marked with a painted steel bar driven into the channel bank. After harvest, we returned to these locations and repeated the grab samples. Comparisons of the pre- and post-harvest grab sample size distributions are shown in Figures 4, 5, and 6. Because of the additional channel roughness created by the logging debris,

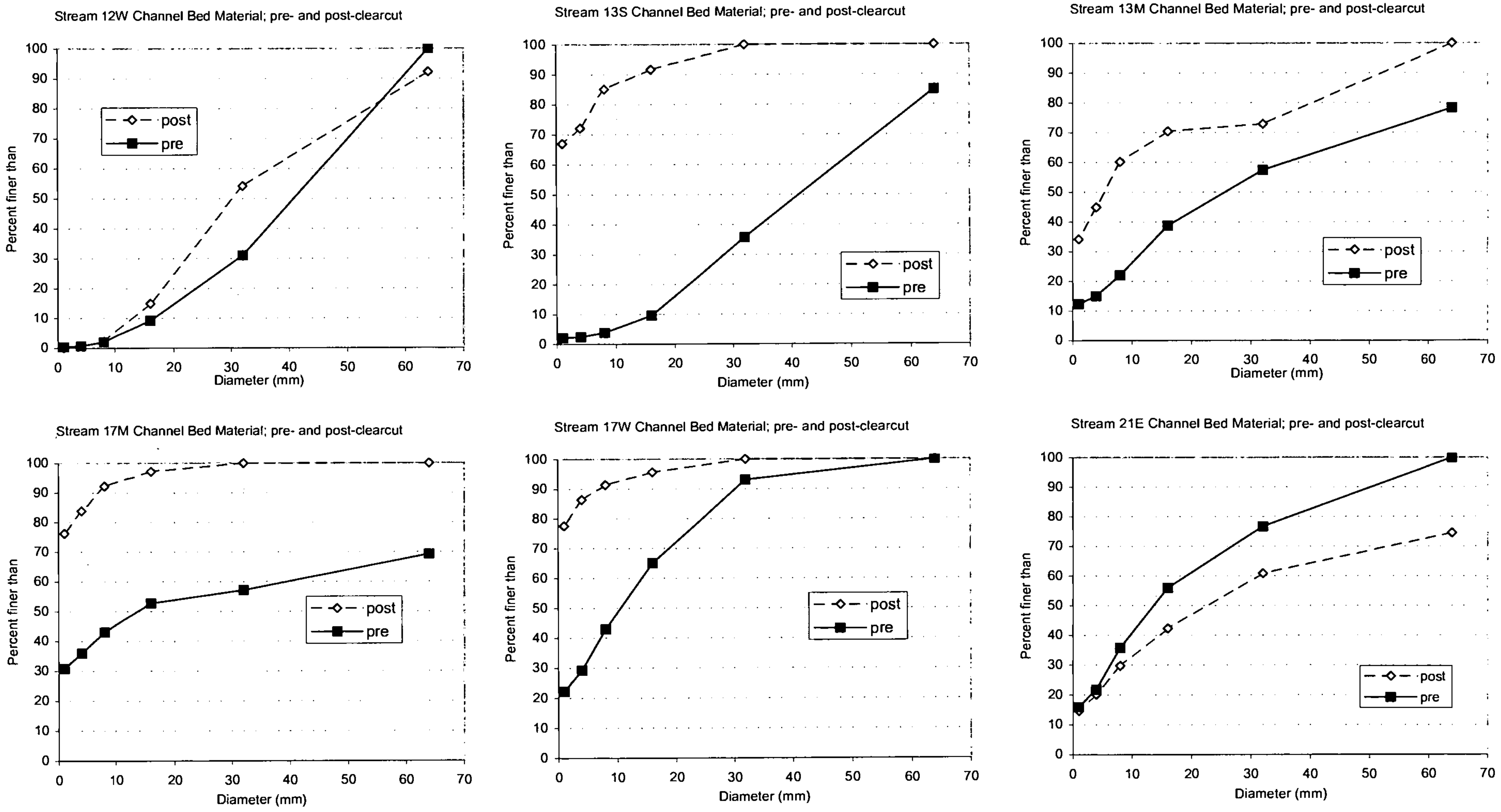

Figure 4. Particle Size Distributions Before and After Timber Harvest in the Clearcut Streams. Particle size distributions were based on sieving of three grab samples collected at the same randomly-selected locations before and after harvest.

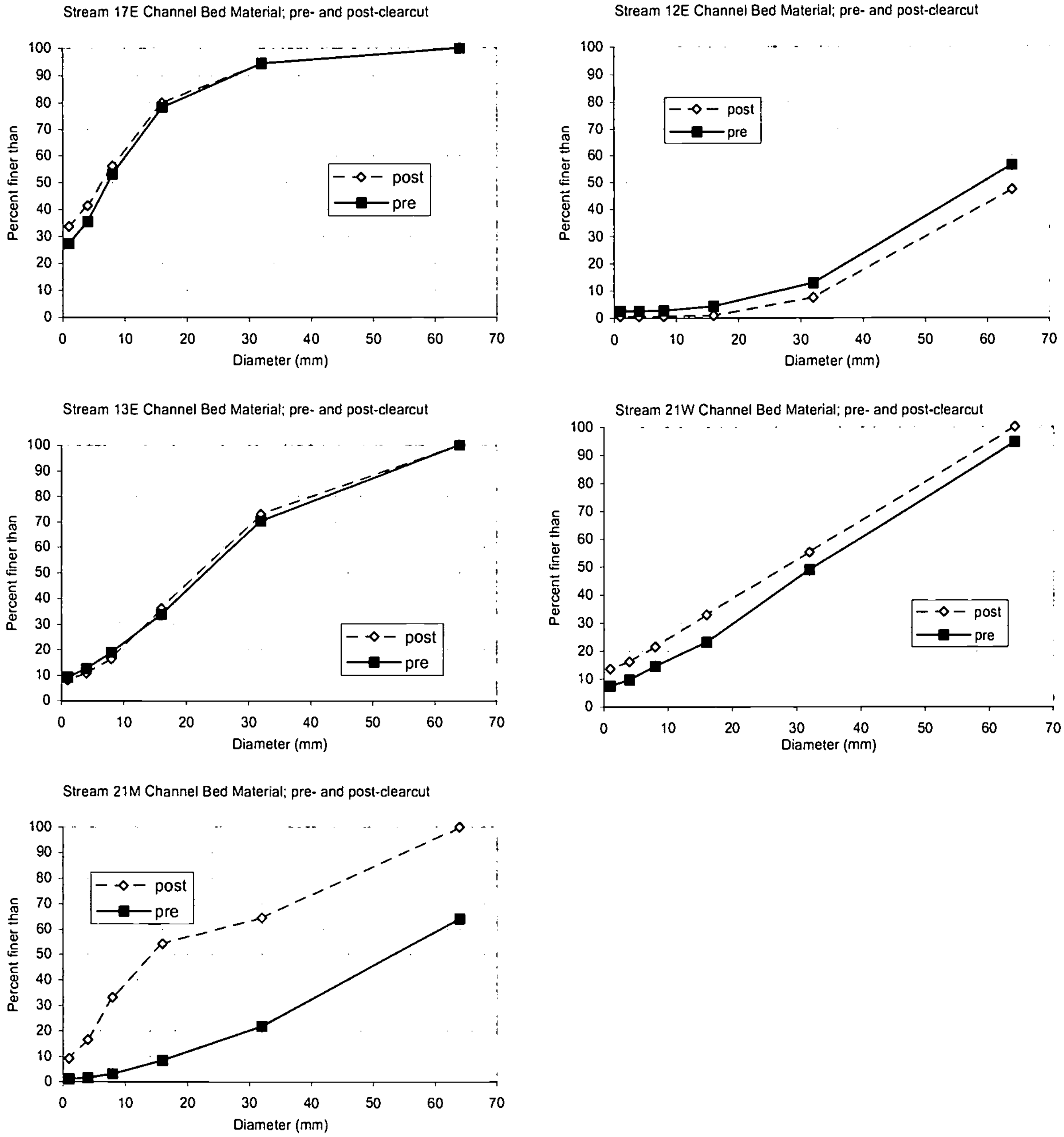

Figure 5. Particle Size Distributions Before and After Timber Harvest in Three Fully-Buffered Streams (17E, 13E, and 21M) and Two Streams With Unusual Buffer Conditions (12E and 21W). Stream 12E was buffered only in the lowest section of the reach, and stream 21W was buffered with a poorly stocked stand of small red alder. All of the grab samples in stream 12E were taken from the buffered portion of the reach. Particle size distributions were based on sieving of three grab samples collected at the same randomly-selected locations before and after harvest.

fine sediments were trapped within the clearcut channels. While we could not quantify bank failures, visual reconnaissance indicated the logging had caused a number of small bank failures along the clearcut streams. These small bank failures contributed to the sediment loading of these streams. As a result of the organic roughness and the additional bank failures, the substrate size distributions in all of the clearcut channels shifted toward finer particles. The average percentage of fine sediments in the clearcut streams increased from 12 to 44 percent. We ran a two-way ANOVA (time x treatment) for percent fines and the only significant change from pre- to post-harvest conditions was in the clearcut streams (Figure 7). We also ran a two-way ANOVA on median particle size, but it did not detect a significant difference in D_{50} before and after harvest in the clearcut streams. Median particle size in the post-harvest clearcut

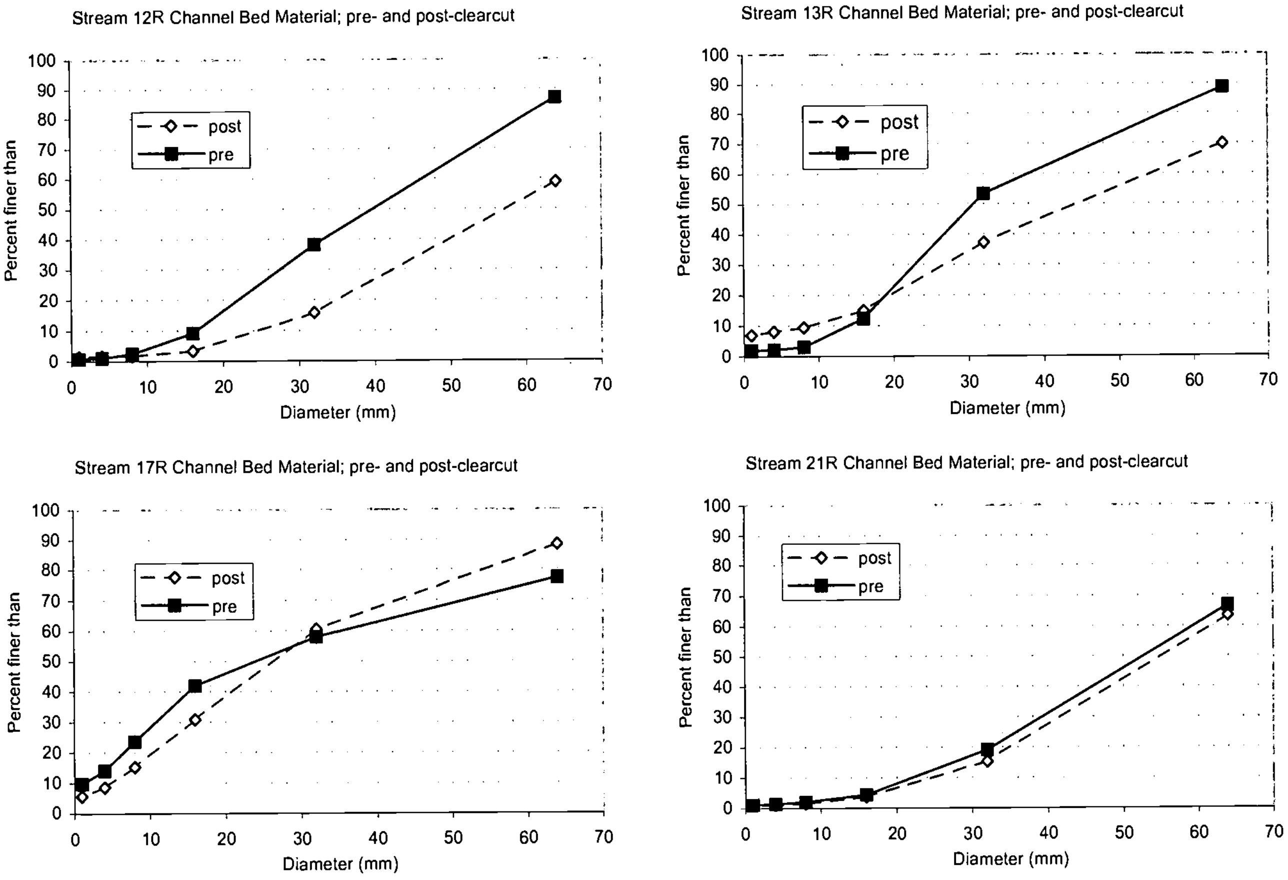

Figure 6. Particle Size Distributions Before and After Timber Harvest in the Four Reference Streams. There is some year-to-year variation in particle size distributions potentially due to differences in the flow regime and due to sampling variation.

streams was significantly lower than in the post-harvest reference streams according to a Tukey multiple comparison (Figure 8). While the median particle size in the clearcut streams decreased from 24 mm to 10 mm after harvest, a paired t-test yielded a p-value of 0.078, so the reduction in median particle size is not statistically conclusive due to the high variability in the pre- and post- harvest sample sets. However, this low p-value, coupled with our observations of channel conditions, strongly suggests a reduction in D_{50} in the clearcut streams due to trapping of fine sediments by the organic debris.

Particle size distributions were almost unchanged in most of the buffered and all of the reference streams as shown in Figures 5 and 6. One of the buffered streams (21M) showed a significant shift toward finer materials. This stream received drainage from a logging road and a landing. In summary, the riparian buffers worked well to maintain pre-harvest habitat and sediment characteristics in their streams. Few deleterious structural habitat changes were observed in the buffered streams in the summer after harvest.

Characteristics of Woody Debris Covering the Clearcut Streams

Seventy-five percent of the large woody debris that covered and buried the channel after clearcutting was between 10 cm and 20 cm in diameter and only 8.6 percent was greater than 30 cm in diameter (Figure 8). The larger, commercially valuable pieces of wood have been yarded from the site. We could not determine a way to quantify either the volume, mass, or piece frequency of woody material within the time we had available for field surveys. It is safe to say, however, that the wood input to the clearcut streams was massive. We determined the woody debris size distribution by stretching a tape longitudinally over the channel and measuring the diameter of each piece of wood touched by the tape. Essentially, we developed a size distribution of the surface wood larger than 10 cm diameter.

Since fine woody debris and woody debris less than 20 cm in diameter are effective in creating steps and habitat in small streams (chesney, 2000; Jackson and

Sturm, 2001), and since these materials are copious in the clearcut streams, the near- and mid-term outlook for maintaining and creating channel steps and sediment storage in the clearcut streams is high. Continued monitoring is necessary to evaluate how fluvial transport and decay affect in-channel woody debris over time.

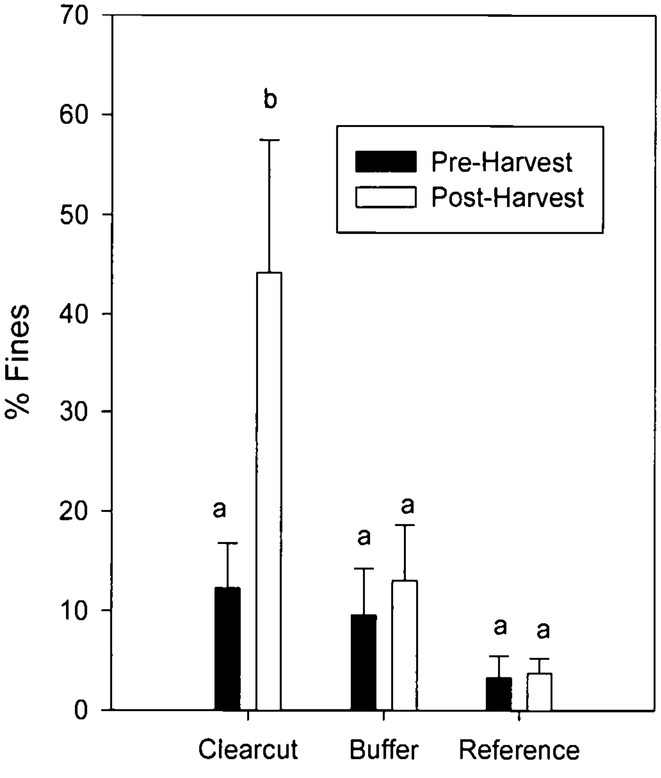

Figure 7. Results of Two Way (time x treatment) ANOVA of the Percentage of Fines in the Channel Bottom. Bars show mean of each group and error bars show the standard error of the mean. Groups which do not share a letter are significantly different according to Tukey multiple comparison. The percentage of fines was determined from sieving three grab samples collected at the same randomly-selected locations before and after harvest. The percentage of fines in the post-harvest clearcut streams is greater than in all other groups, which could not be statistically differentiated from one another.

Stream Temperatures

We monitored pre- and post-harvest temperatures in the study stream to assess the effect of harvest on water temperature. The summer of 1999 was much cooler than the summer of 1998, and this was reflected in the stream temperatures. Using the hourly stream temperatures from the reference streams, relative frequency histograms were made for 1998 and 1999 (Figure 10). The temperature histograms for the reference streams clearly demonstrate the natural differences in the two summers.

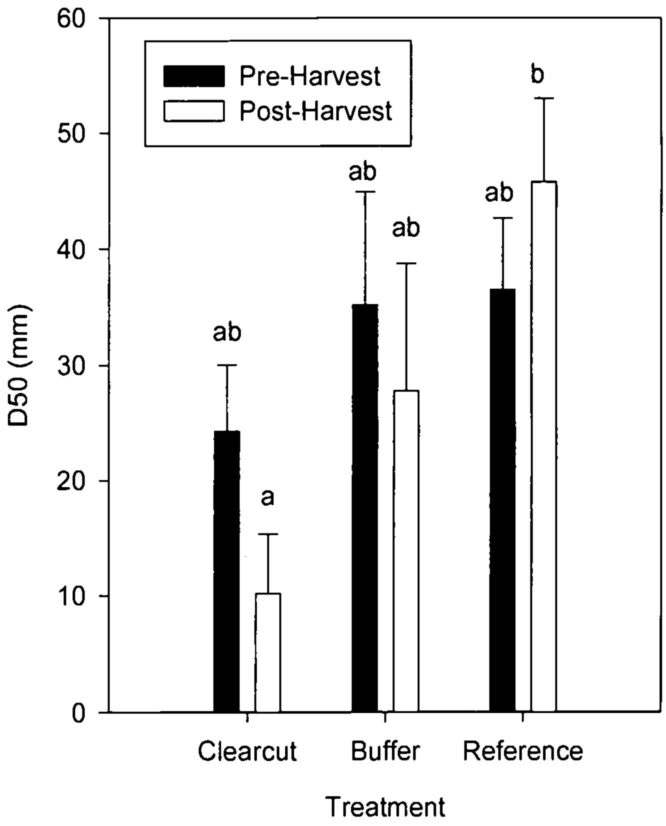

Figure 8. Results of Two-Way (time x treatment) ANOVA of the Median Particle Diameter in the Channel Bottom. Bars show mean of each group and error bars show the standard error of the mean. Groups which do not share a letter are significantly different according to Tukey multiple comparison. The median particle diameter was determined from sieving three grab samples collected at the same randomly-selected locations before and after harvest.

Because of the large differences in 1998 and 1999 summer temperatures, the temperature ranges observed before and after harvest often had little to no overlap, which made it more difficult to assess the effect of timber harvest on temperature. From the hourly temperature observations, daily maximum temperatures were calculated for the pre-harvest summer of 1998 and the post-harvest summer of 1999. The daily maximum stream temperatures were then plotted against the appropriate reference stream and a regression equation was calculated (Figures 11 and 12). The slopes of the pre- and post-harvest regression lines were compared using a Student's t-test in a method analogous to using a paired t-test to compare two population means (Zar, 1984). This test allowed us to determine if pre- and post-harvest years have significantly different slopes. Using the regression equations, changes in stream temperature were calculated based on a reference stream temperature of 11°C which was generally within or near the overlapping range of the 1998 and 1999 data. This approach was used to minimize the amount of extrapolation used to assess the temperature shifts in the streams.

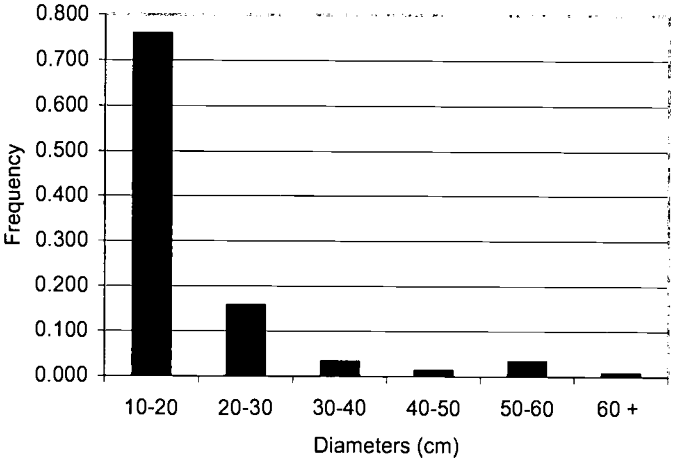

Figure 9. Histogram of Diameters of Large Woody Debris Left in the Clearcut Streams After Yarding. Distribution determined by stretching a tape longitudinally over the channel and measuring the diameter of each piece of wood greater than 10 cm diameter touched by the tape.

Temperature impacts of timber harvest are summarized in Table 3. Of the seven clearcut streams, three exhibited no statistically significant difference in stream temperature, one became cooler (-1.1°C), one became slightly warmer (+0.8°C), and the remaining two streams became both cooler and warmer depending on location in the stream. The 12W stream and the 21E stream were longer than the other streams, and two HOBOs were placed in these streams. In both streams, the temperatures at the upper HOBOs became cooler (-2.2 and -1.7°C) while the temperatures at the lower HOBOs became a lot warmer (+5.2 and +15.1°C). In short, the temperature in only partial sections of only two of seven clearcut streams increased enough to have a deleterious effect on amphibians. Four of the seven streams either did not change or became cooler. This is strongly counter to the conventional wisdom regarding the effects of clearcutting on stream temperature. In this case, temperatures of the clearcut streams were protected by the layer of slash that was deposited over these streams. The slash effectively shaded the stream and acted as an insulating blanket. Temperature changes in the three buffered streams were not dramatic. Two became warmer (+1.6 and +2.4°C) and one became slightly cooler (-0.3°C). The buffers prevented slash from burying these streams, but the remaining overhead canopy prevented large temperature changes.

Despite the initial study design, only one nonmerchantable buffer was created in the study. It did prevent slash burial of the stream, but it provided less overhead canopy than the full buffers. Two HOBOs were placed in this stream, and they both detected sizeable temperature increases (+3.7 and +6.6°C).

DISCUSSION

In the relatively steep topography of the study sites, logging debris tended to accumulate at the bottom of slopes and thereby bury the headwater streams that lacked riparian buffers. During logging, the cutters drop the tops of the trees downslope, and thus the stream valleys are covered by the tops of trees cut from both sides of the valleys. The tops and the branches are removed prior to yarding of the logs, and these tops and branches remain where they fall, which is on top of the streams. Consequently, the dramatic morphological effect of clearcutting across headwater streams was the covering or burial of streams with one to two meters of organic debris. This organic debris consisted of whole branches including needles, small twigs, and logs.

In discussions of our observations with timber managers, we have heard many people remark that slash burial of streams does not happen on their lands or their operations, but informal surveys indicate that slash burial of unbuffered streams is ubiquitous when side slopes are steep or even moderate. Even though the primary author had conducted many surveys of streams in commercial timber production land, he was initially surprised by this finding. It is easy to see why this fact has been overlooked. After the logs have been yarded, the slash burial is often so complete that it is not apparent from most vantage points that a stream once existed on the site.

The riparian buffers served as a fence to keep the organic debris out of the streams, and they served to protect the streambanks. The buffered streams experienced little to no addition of logging debris, and generally exhibited little to no bank failure or erosion. Some of the mature trees left in the buffer were blown down by windstorms, and these trees spanned the channels. In some cases, soil from the windthrow entered the buffered channels. In general, the morphology of the buffered channels changed little after clearcutting. One member of our study team visited the study sites in the summer of 2000 and observed

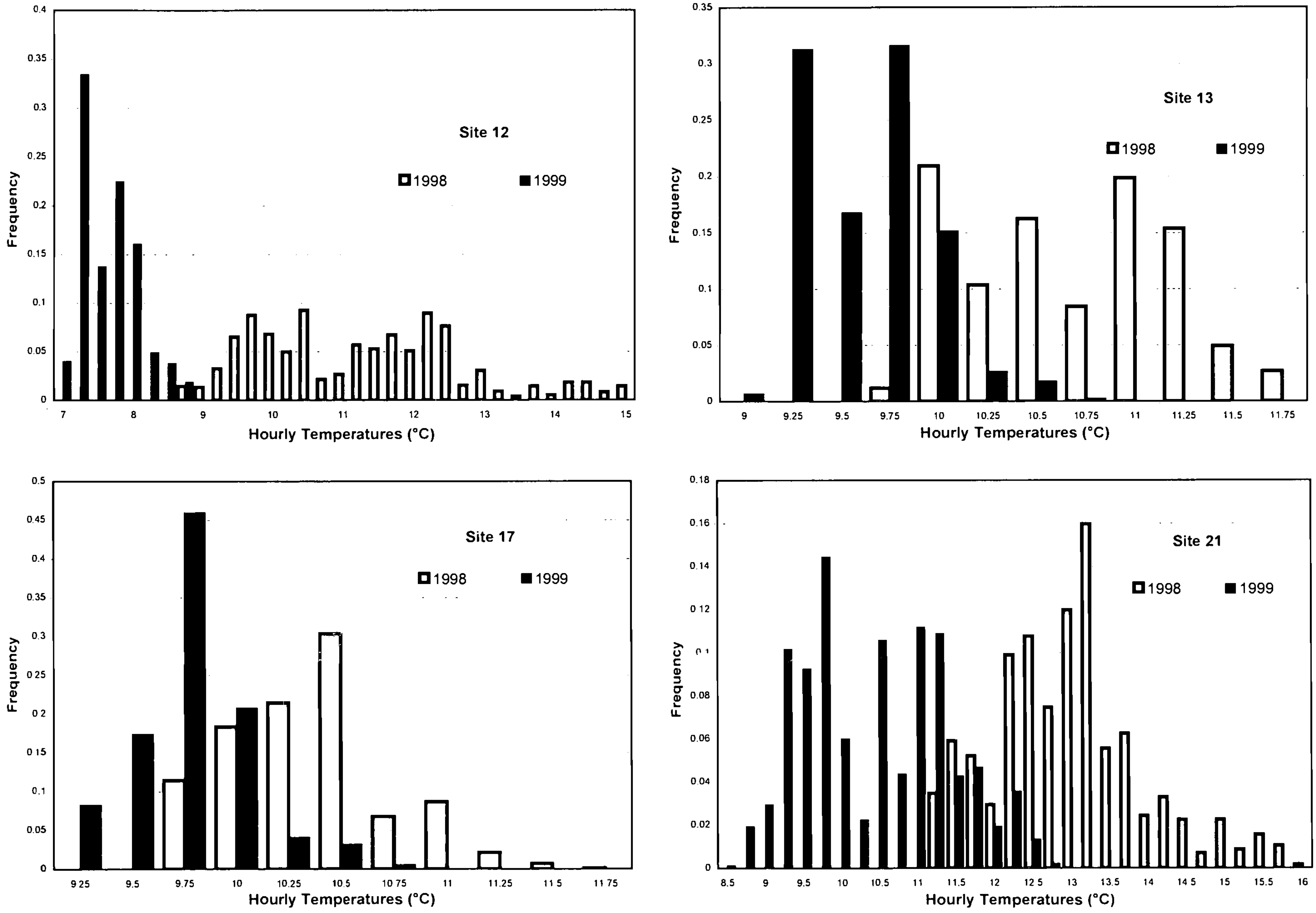

Figure 10. Histogram of Hourly Temperatures in the Reference Streams at Each Site During the Summers of 1998 and 1999. The summer of 1999 was much cooler and this was reflected in the water temperatures.

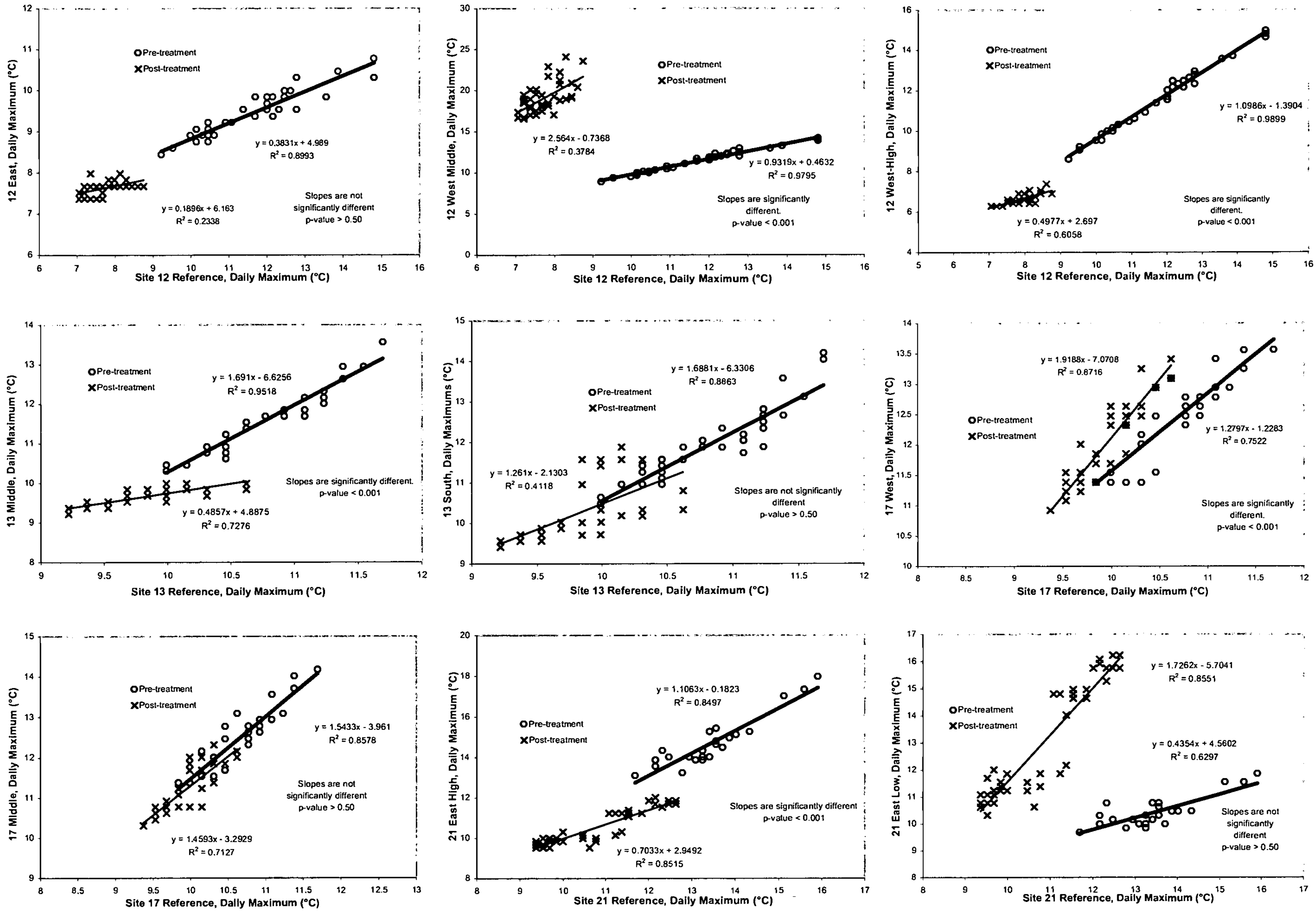

Figure 11. Regressions of Daily Maximum Water Temperatures Between Clearcut and Reference Streams Before and After Timber Harvest.

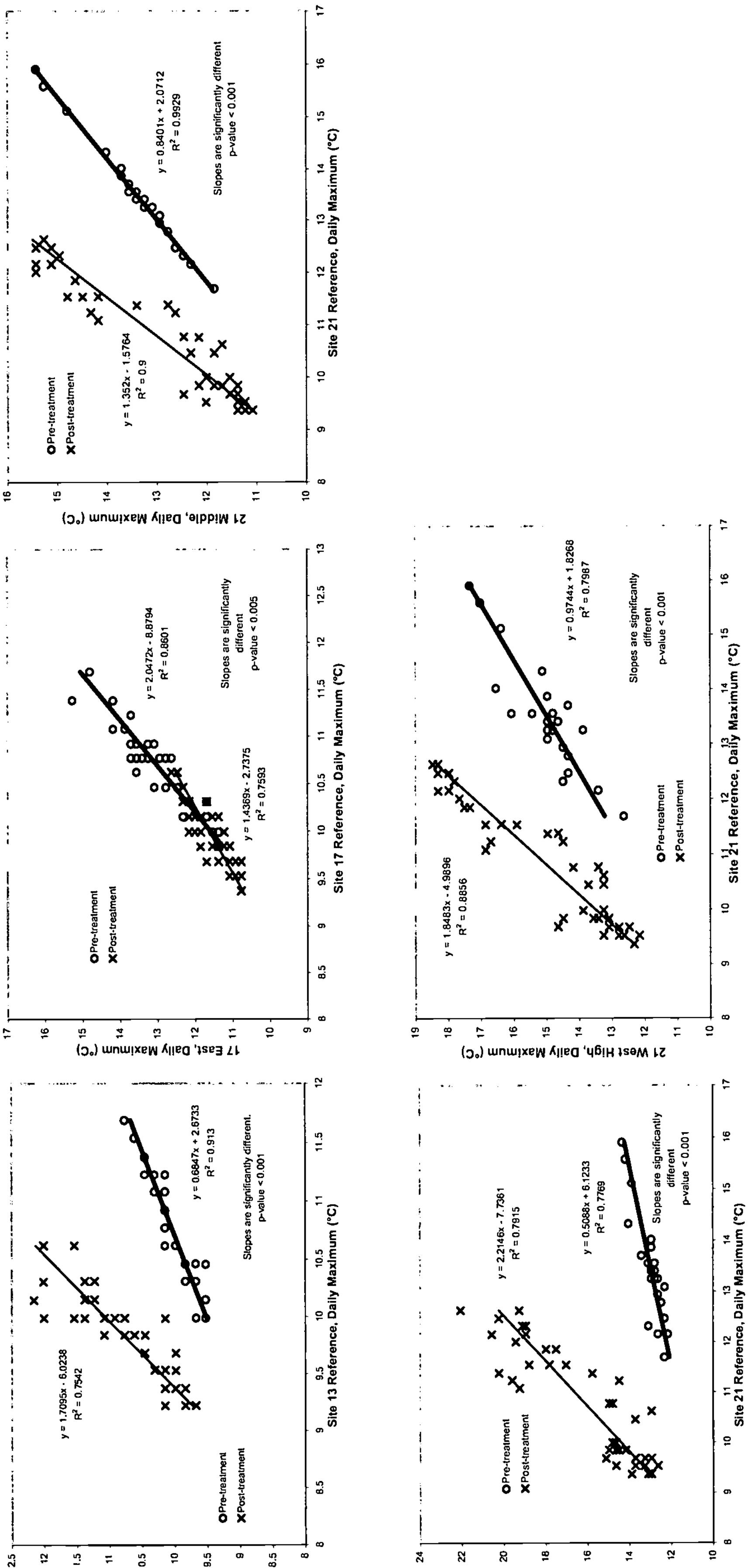

Figure 12. Regressions of Daily Maximum Water Temperatures Between Buffered and Reference Streams Before and After Timber Harvest.

TABLE 3. Estimates of Temperature Impacts. Using the regression equations, changes in stream temperature are calculated based on a reference stream temperature of 11°C. This temperature is generally within or near the overlapping range of the 1998 and 1999 data and was chosen to avoid extrapolating either the pre- or post-harvest regression relationships beyond their data range.

Stream	Treatment	Pre-Harvest Temperature	Post-Harvest Temperature	Temperature Change °C
12W-high	Clearcut	10.69	8.17	-2.5
12W-middle	Clearcut	10.71	27.46	+16.8
12E	Clearcut	No significant difference in reference stream relationship		–
13S	Clearcut	No significant difference in reference stream relationship		–
13M	Clearcut	11.98	10.23	-1.8
17W	Clearcut	12.85	14.04	+1.2
17M	Clearcut	No significant difference in reference stream relationship		–
21E-high	Clearcut	11.99	10.69	-1.3
21E-low	Clearcut	9.35	13.28	+3.9
13E	Buffer	10.21	12.78	+2.6
17E	Buffer	13.64	13.07	-0.5
21M	Buffer	11.31	13.30	+2.0
21W-high	Nonmerchantable Buffer	12.50	15.34	+2.8
21W-low	Nonmerchantable Buffer	11.72	16.62	+4.9

that significant blowdown had occurred in all of the buffers. The blowdown had destabilized channel banks and increased sediment loading to the streams. We plan to return to these streams in 2001 and quantify these blowdown effects and the evolution of channel morphology.

The massive addition of organic debris to the clearcut streams had many channel and ecological effects. The slash protected the channel from solar radiation and also acted as thermal insulation, so most of the clearcut streams experienced little to no temperature impact from timber harvest. The hydraulic roughness provided by the conifer needles, twigs, and branches trapped fine sediment in the channels. In some cases, the channel became indistinct, and the water flowed through a matrix of mixed organic and inorganic materials. As a result, particle size distributions within the former channel shifted toward finer sediments.

The potential biological implications of the changes to the clearcut channels are numerous. In the near term, downstream sediment movement from unbuffered clearcut streams is greatly reduced because the organic material traps sediment in the channel. Particle size distributions in downstream reaches may become coarser until the organic debris in the unbuffered streams decays and allows for renewed downstream sediment movement.

The fining of the bed material and alteration of the habitat is likely to be locally detrimental to populations of certain amphibian species. Our amphibian surveys indicated that *Ascaphus truei* and *Dicamptodon* populations severely declined in the clearcut streams immediately after harvest (Cross, 2001). The habitat becomes completely unsuitable for *Ascaphus truei* larvae which need fast moving water and cobble habitat. Fine sediments fill in the rocky crevices preferred by *Dicamptodon*. The fining of the substrate potentially affects gill function in some aquatic salamanders, and this may explain observed reductions in *Dicamptodon* abundance following harvest. Moist and mossy habitat near the channels, suitable for *Plethodon vandykei* and *P. dunni*, are eliminated in the short term by clearcut harvest. Water temperatures for downstream salmonid populations are unlikely to be affected by clearcut harvest because the slash covering the headwater streams protects against temperature increases. In the special cases of deep organic burial of steep and powerful streams, the organic debris may contribute to the initiation of channel-scouring debris flows.

Our related macroinvertebrate sampling revealed several surprises (Haggerty, 2000; Haggerty *et al.*, 2001). In the first summer after logging, we found significant increases in overall macroinvertebrate densities, collector densities, shredder abundance and biomass, and organic and inorganic matter accretion. However, these responses were transient and were not detected one year following logging. There are several possible explanations for the initial increase in macroinvertebrate densities in the clearcut streams relative to the reference streams, including wood addition and increased amounts of organic and inorganic matter accretion after logging. These conditions are likely to change rapidly over the next few years as the logging debris decays or material is mobilized during high flows.

This study has observed only immediate effects of logging on physical channel conditions. Of course, the organic material in the channel will decay and be physically broken down by fluvial action. Much of this organic debris will move downstream. Following the decay and flushing of much of the small organic material, the remaining logging debris will provide an abundance of organic material to create channel steps and organic debris dams. While this is going on, shrubby vegetation will grow on the channel margins until it is shaded out by the developing canopy of the new conifer stand. Whether these new debris dams will hold until the new forest begins to deliver new supplies of woody debris is unknown. From this study, we cannot predict how channel conditions will evolve over time.

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