North American Journal of Fisheries Management 6:24–31, 1986

Application of a Method for Assessing the Impact of Watershed Practices: Effects of Logging on Salmonid Standing Crops

JAMES W. A. GRANT

Department of Zoology, University of Guelph
Guelph, Ontario N1G 2W1, Canada

JOHN ENGLERT AND BRIAN F. BIETZ

Beak Associates Consulting Limited, 2635—37 Avenue, NE
Calgary, Alberta T1Y 5V7, Canada

Abstract.—Preliminary studies on three control streams (unaffected by logging) indicated that there were no significant intrastream differences in the total biomass of Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*), and brook trout (*Salvelinus fontinalis*) between discrete areas of similar habitat. Therefore, total salmonid biomass should be a good indicator of stream habitat quality for salmonids and useful in assessing the impacts of watershed practices. Total salmonid biomass was used to assess the effect of logging disturbances, including stream crossings, clear-cuts, and bank modification, on the salmonid populations of 10 streams in New Brunswick and Nova Scotia. This biomass was measured at pairs of logging-disturbed and upstream control areas of the 10 streams. Salmonid biomass decreased significantly downstream of two stream crossings, probably because of increased siltation, while seven clear-cuts and one bank modification along the other eight streams had no significant effect on salmonid biomass. Removal of the canopy cover was associated with increases in the fork length or weight at age, or both, of juvenile Atlantic salmon but had no consistent effect on the size at age of brook trout.

Logging and its associated practices can have a major impact on stream ecosystems. Of particular concern are the negative effects of increased siltation (Burns 1970, 1972; Brown and Krygier 1971; Barton 1977; Beschta 1978), higher water temperatures (Hall and Lantz 1969; Brown and Krygier 1970), and increased variation in discharge (Lynch et al. 1977; Harr and McCorison 1979). However, some recent studies have demonstrated that logging, through the removal of canopy cover, can also increase primary production, resulting in an increase in the standing crop of macroinvertebrates and fish (Chapman and Knudsen 1980; Murphy and Hall 1981; Murphy et al. 1981).

In order to optimally predict and quantify the effect of a watershed practice on a stream, preimpact, during-impact, and postimpact data generally are required for the affected and a control watershed (Green 1979). Several long-term studies of the effects of logging on stream ecosystems have used this design: Alsea Watershed Study (Moring 1975); Carnation Creek Project (Scrivener and Brownlee 1981; Tschaplinski and Hartman 1983); and Nashwaak Experimental Watershed Project (Krause and King 1981). However, there are a number of practical limitations to the optimal impact study design: (1) long-term studies are expensive, (2) the data generated from case studies of single watersheds may not apply to the general situation, and (3) regulatory agencies must often react after the impact has occurred.

As an alternative to the optimal design for assessing the impacts of watershed practices, Hall et al. (1978) recommended using paired sites, each comprised of a downstream affected site and an upstream control site, on a number of streams. Because a variety of sites can be selected, this "extensive post-treatment" design was felt to provide the broadest spatial and temporal perspective for assessing the impact of a watershed practice. The primary disadvantage of the study design is the assumption of no differences between the paired sites before the treatment.

In this study, we first tested this critical assumption, and then applied the extensive post-treatment study design to determine the effects of some logging practices on the salmonid populations in the streams of the Maritime Provinces. We assumed, a priori, that the total biomass of salmonids would be a good indicator of stream habitat quality. Because salmonids are at the top of the food web, their biomass should reflect the overall response of the stream ecosystem to the impact of logging (Murphy and Hall 1981).

Test of the Study Design

The study design called for comparisons of salmonid standing crops in pairs of logging-disturbed

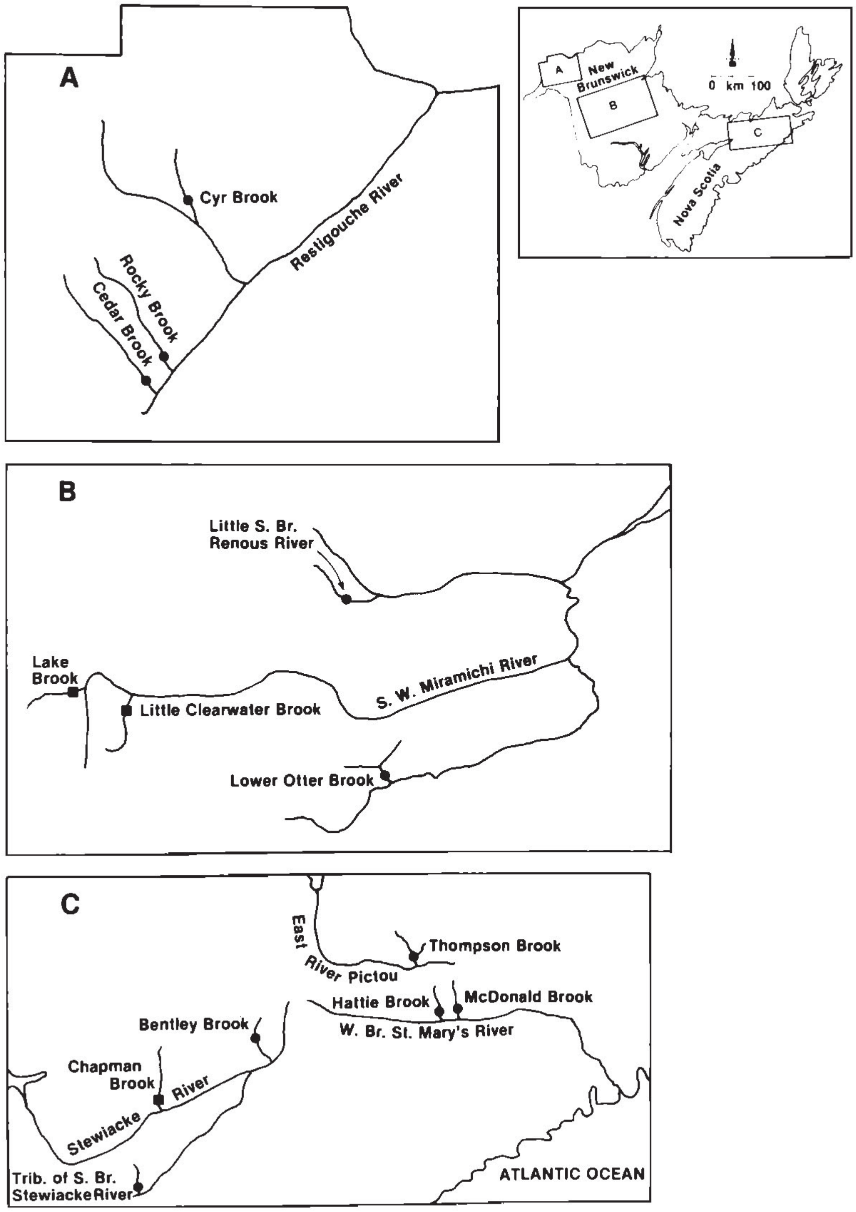

FIGURE 1.—Map showing study areas on the three control streams (squares) and 10 experimental streams (circles) in Nova Scotia and New Brunswick.

and control areas from 10 small streams in Nova Scotia and New Brunswick. Implicit in the design was the assumption that the habitat of the upstream control and downstream disturbed areas was sufficiently similar that differences in total salmonid standing crop could be attributed solely to the effects of logging. To test this assumption, it was necessary to show that the salmonid standing crop within pairs of similar habitats in undisturbed streams was not significantly different.

Methods

The study design was tested on three control streams that were undisturbed by logging (Figure 1; Table 1). Two similar areas in each stream, separated by 300–800 m, were selected. The paired sites were matched for stream width, water depth, water velocity, substrate size, riffle-to-pool ratio, shoreline vegetation, and amount of bank undercutting. A general description of the control streams is presented in Table 1.

Each area was divided into five quadrats of equal length (10–15 m). The downstream and upstream ends of each area were blocked off with barrier nets of 1.27-cm stretched mesh. A third net was used to section off the first quadrat at the downstream end of the area. Quadrats were sampled from downstream to upstream within an area. One

TABLE 1.—General description of the control streams in New Brunswick and Nova Scotia.

Stream	Stream order	Gradient (m/km)	Discharge (m^3/s)	Dominant[a] substrate	Distance between areas (m)
Chapman Brook	3	13.8	0.29	Cobble	800
Little Clearwater Brook	3	13.3	0.51	Boulder	400
Lake Brook	3	3.3	0.17	Pebble	300

[a] After Hynes (1970).

area, consisting of five quadrats, was sampled per day and one stream, consisting of two areas, was sampled in 2 consecutive days. The three control streams were sampled from July 22 to July 31, 1981.

Fish collection was done by a three-person crew using Smith-Root Mark VII, Mark VIII (450 V, 53 Hz), or Coffelt BP-3 (500 V, self adjusting frequency) electrofishing units. Paired areas within a stream were sampled with the same electrofishing unit. Five standard sweeps were made per quadrat, each in a downstream direction. Few fish were captured on the fourth or fifth sweeps. Following each sweep, the downstream barrier net was checked for fish. We assumed that this procedure sampled the same proportion of the standing crop in each quadrat within a stream. We did not catch enough brook trout (*Salvelinus fontinalis*) or brown trout (*Salmo trutta*) to calculate reliable population estimates in many of the streams even though they often contributed a large percentage of the total salmonid biomass of a quadrat.

Fish were anaesthetized with sodium bicarbonate (Booke et al. 1978) and measured for fork length in the field. The first 20 juvenile Atlantic salmon (*Salmo salar*), the first 20 brook trout, and all brown trout per quadrat were preserved in 10% formalin. Brook trout and brown trout larger than 150 mm were weighed, sampled for scales, and immediately released. Other fish to be released were held in live buckets until sampling was completed. Preserved fish were weighed in the laboratory. Subsamples of fish that were measured before and after preservation in formalin indicated that the juvenile salmonids decreased in length by 4%. Weight of the released fish was estimated from corrected length–weight regressions for each study area and species. Fish were aged by length-frequency analysis.

Brown trout, which were rare, were included with brook trout in population density and biomass calculations because of the ecological similarity of the two species (Scott and Crossman 1973). Two-tailed Student's t-tests ($P = 0.05$) were used to compare population density and biomass within streams. Mann-Whitney U-tests were used when the data were heteroscedastic.

Results

There were no significant differences in salmonid biomass (g/m^2) between upstream and down-

TABLE 2.—Intrastream comparisons of salmonid biomass and density in the control streams. Asterisks indicate the upstream mean is significantly different from the downstream mean: *$P < 0.05$; **$P < 0.001$.

Stream	Biomass (g/m^2) Downstream (mean±SD)	Biomass (g/m^2) Upstream (mean±SD)	Density (number/100 m^2) Downstream (mean±SD)	Density (number/100 m^2) Upstream (mean±SD)
		All salmonids		
Chapman Brook	2.4±1.8	3.3±1.4	69.7±15.8	84.1±21.7
Little Clearwater Brook	5.2±0.9	4.2±0.8	121.5±9.5	82.2±12.4**
Lake Brook	4.7±1.1	5.1±0.8	146.6±15.2	172.2±27.1
		Atlantic salmon		
Chapman Brook	1.5±0.3	2.5±0.7*	67.6±15.4	82.1±21.2
Little Clearwater Brook	4.5±0.5	3.5±0.6*	113.7±6.7	79.2±11.9**
Lake Brook	4.4±0.9	4.5±1.0	141.0±12.9	162.8±29.5
		Brook and brown trout		
Chapman Brook	0.9±1.6	0.8±1.0	2.1±1.9	2.0±2.1
Little Clearwater Brook	0.4±0.4	0.6±0.3	7.8±3.6	9.4±2.2
Lake Brook	0.8±0.7	0.6±0.3	5.6±4.4	9.4±5.5

TABLE 3.—General description of the 10 experimental streams in New Brunswick and Nova Scotia.

Stream	Stream order	Gradient (m/km)	Discharge (m^3/s)	Dominant substrate	Distance between areas (m)
Little South Branch Renous River	3	13.2	1.90	Boulder	120
Tributary of South Branch Stewiacke River	2	10.2	0.01	Gravel	125
Lower Otter Brook	3	3.4	0.22	Pebble	120
Bentley Brook	3	7.3	0.01	Cobble	1,500
Hattie Brook	2	13.8	0.01	Cobble	70
McDonald Brook	3	6.8	0.06	Pebble	320
Cyr Brook	3	13.2	3.00	Cobble	200
Thompson Brook	2	33.9	0.01	Bedrock	210
Cedar Brook	3	6.8	0.36	Pebble	250
Rocky Brook	2	17.9	1.47	Cobble	300

stream areas within any of the three streams (Table 2). However, there were significant differences in the biomass of Atlantic salmon in two of three streams. There were no significant intrastream differences in biomass of brook trout and brown trout (Table 2).

The density of all salmonids (number/100 m^2) was significantly greater downstream than upstream in Little Clearwater Brook (Table 2), but there were no significant differences in density of all salmonids in Chapman Brook or Lake Brook. The density of Atlantic salmon also was greater downstream than upstream in Little Clearwater Brook. There were no intrastream differences in the density of Atlantic salmon in the other two streams, or in the density of brook and brown trout in any of the streams.

Mean fork length of Atlantic salmon fry (age 0+) was significantly different in two of the three streams. Fork length was greater downstream (mean = 41.6 mm) than upstream (40.4 mm; $P < 0.001$) in Chapman Brook and greater upstream (47.6 mm) than downstream (46.9 mm; $P < 0.05$) in Little Clearwater Brook. There were no significant intrastream differences in fork length at age of brook trout or Atlantic salmon parr (ages 1+–3+). There also were no intrastream differences in weights of brook trout or juvenile Atlantic salmon.

Validity of the Study Design

Our results indicated that there were no significant differences in total salmonid biomass between pairs of similar habitats within a stream. Therefore, the basic, but previously untested, assumption of the extensive post-treatment design was met. We should note that great care went into the selection of the physically similar pairs of habitats during the test of the study design and in the following tests. A less meticulous approach in selecting paired sites to assess the effects of any environmental disturbance could invalidate the experimental design.

There were significant intrastream differences in the biomass of Atlantic salmon. However, it is inappropriate to consider only one salmonid species independently of the others because all three defend interspecific territories, excluding each other from parts of the total habitat (Kalleberg 1958; Gibson 1978; Fausch and White 1981).

There also were significant intrastream differences in the density of salmonids. Density will be influenced by age-specific differences in habitat preferences and social interactions among year classes (Symons and Heland 1978) and, therefore, will be affected by the age structure of the population. Intrastream differences in salmonid density without parallel differences in biomass are probably more of a reflection of variation in microhabitat rather than differences in general habitat quality. There was also significant intrastream variation in the fork length of Atlantic salmon fry, perhaps because of intraspecific competition.

Because the density of all salmonids, the biomass of Atlantic salmon, and the fork length at age of Atlantic salmon fry all varied significantly in at least one of the control streams, they are not reliable indicators of habitat quality for salmonids. Nevertheless, these variables may be of value in conjunction with measures of biomass in interpreting how logging activities affect salmonid populations.

We slightly modified the extensive post-treatment design of Hall et al. (1978) by subdividing each of the paired sites into five quadrats, which allowed for statistical testing of the effects of each

TABLE 4.—Description of logging disturbances at downstream sites of experimental streams.

Stream	Description	Year of impact
	Stream crossings	
Little South Branch Renous River	Bridge crossing, gravel road approach with 10° slope, disturbed area 30-m downstream	1980
Tributary of South Branch Stewiacke River	Bridge crossing, gravel road approach with 25° slope, disturbed area 10-m downstream	1971
	Bank modification	
Lower Otter Brook	One bank straightened for 75 m and shoreline vegetation removed	1981
	Clear-cuts	
Bentley Brook	150 hectares logged	1980
Hattie Brook	4 hectares logged	1980
McDonald Brook	4 hectares logged on one bank	1979
Cyr Brook	63 hectares logged	1979
Thompson Brook	20 hectares logged	1970
Cedar Brook	100 hectares logged	1973
Rocky Brook	150 hectares logged	1971

watershed practice. This modified design should be particularly useful in assessing the effects of point-source disturbances when predisturbance data are unavailable.

Effect of Logging on Salmonid Standing Crop

The study design was applied to 10 experimental streams from five different watersheds (Figure 1; Table 3). Forestry maps were used to prepare a preliminary list of streams with logging-disturbed and undisturbed areas. Over 100 streams in New Brunswick and Nova Scotia were visited before the final 10 streams were selected.

The control area for each disturbance was located upstream, following Hall et al. (1978). Control areas were chosen to be as similar to the disturbed area as possible except for the direct effects of logging. The paired sites were matched for all physical characteristics used in the test of the study design except for shoreline vegetation and substrate type, which were often altered by logging activities.

Sampling methods were identical to those used in the test of the study design. The percentage of the stream quadrat that was shaded from direct sunlight (percent canopy cover) was estimated from photographs and sketches. These streams were sampled from August 28 to September 14, 1981.

TABLE 5.—Percent canopy cover (mean ± SD) of disturbed and control areas of 10 experimental streams.

Stream	Disturbed	Control
Little South Branch Renous River	20±4	21±10
Tributary of South Branch Stewiacke River	56±14	83±10
Lower Otter Brook	18±6	35±9
Bentley Brook	13±8	89±11
Hattie Brook	8±5	77±10
McDonald Brook	13±8	74±17
Cedar Brook	25±12	39±7
Cyr Brook	22±6	34±5
Thompson Brook	7±10	78±3
Rocky Brook	5±6	82±8

Description of Logging Disturbances

We had planned to include a variety of logging disturbances of various ages but the final choice of 10 streams usually was dictated by the presence of a suitable control area. Large clear-cuts often extended to the headwaters of a watershed and could not be included in our study because of the lack of a suitable upstream control area. The extensive post-treatment design may be more appropriate for assessing the impacts of localized disturbances rather than major watershed practices. The 10 experimental streams are described in Table 3; the logging disturbances on these streams are described in Table 4.

Two of the logging disturbances were stream crossings (bridges). Deep gullies on either side of both crossings were sources of fine sediments. Visual inspection indicated that sand and silt accumulated in areas of low current downstream of the stream crossing at the tributary of the South Branch of the Stewiacke River (hereafter, Stewiacke River). There was no noticeable increase in fine sediments in the substrate of the disturbed area of the Little South Branch Renous River (hereafter, Renous River), perhaps because of its higher gradient and current velocity. Because flowing water washes away surface sediments, core samples probably would be required to detect and quantify any increases in fine sediments (Adams and Beschta 1980).

A bulldozer apparently had been used to straighten the bank and remove the shoreline vegetation along one bank of Otter Brook. Consequently, percent canopy cover in the control area was about twice that of the disturbed area (Table 5). The logging disturbances at the remaining seven streams were small clear-cuts (4–150 hectares). Disturbed areas were adjacent to the cutover areas. In all cases, the clear-cuts extended to and included

TABLE 6.—Intrastream comparisons of total salmonid biomass and density in logging-disturbed and control areas of 10 experimental streams. Asterisks indicate the control-area mean is significantly different from the disturbed-area mean; *$P < 0.05$, **$P < 0.01$.

Stream	Biomass (g/m^2)		Density (number/100 m^2)	
	Disturbed (mean±SD)	Control (mean±SD)	Disturbed (mean±SD)	Control (mean±SD)
Little South Branch Renous River	3.2±0.3	4.0±0.7*	101.1±18.3	118.2±16.9
Tributary of South Branch Stewiacke River	0.3±0.3	1.3±0.6*	2.7±3.0	11.3±6.5**
Lower Otter Brook	4.0±2.1	5.5±2.9	99.8±20.5	132.1±31.5
Bentley Brook	2.4±1.0	6.0±4.1	96.5±46.3	192.3±49.9*
Hattie Brook	3.5±2.7	1.6±1.3	54.2±23.6	23.1±8.8*
McDonald Brook	1.0±0.4	0.8±0.4	50.7±31.3	48.9±15.4
Cyr Brook	1.1±0.4	1.3±0.4	19.6±4.7	12.7±1.1
Thompson Brook	5.9±1.4	5.2±1.2	243.9±47.9	185.4±19.1*
Cedar Brook	1.0±0.7	2.4±3.0	21.1±15.0	21.7±10.9
Rocky Brook	1.2±0.2	2.1±1.8	25.8±3.3	25.4±13.4

the stream-bank vegetation, drastically reducing the percentage of canopy cover (Table 5).

Results

No significant intrastream differences were found in total salmonid biomass in eight of the 10 streams tested (Table 6). Only in the Renous and Stewiacke rivers were there significant intrastream differences in salmonid biomass. In both cases, the disturbance was a stream crossing and the biomass was greater upstream in the control area than downstream in the disturbed area. There were significant intrastream differences in density of salmonids in four of 10 streams, but no consistent patterns were evident. Stewiacke River and Bentley Brook had higher densities in the control areas, while Thompson and Hattie brooks had higher densities in the disturbed areas.

The fork lengths and weights at age of juvenile Atlantic salmon are compared in Table 7. Atlantic salmon generally were larger in the disturbed areas. For example, the mean fork lengths for age-0+ fish in Bentley and McDonald brooks and age-0+ and -1+ fish in Thompson Brook were significantly greater in the disturbed (clear-cut) areas than control areas. The weights of age-0+ fish also were significantly greater in the disturbed areas of Bentley and McDonald brooks (clear-cuts) and in Lower Otter Brook (bank modification). There were no differences in weight at age of Atlantic salmon in Thompson Brook, despite the differences in fork length. Only the Renous River, where the disturbance was a stream crossing, showed no evidence of an increase in either fork length or weight at age of Atlantic salmon in the disturbed area.

There were no consistent trends in the size of brook trout. Brook trout were significantly different only at Cyr Brook where they were longer and heavier in the control area.

Discussion

Total salmonid biomass decreased significantly downstream of the two stream crossings, probably as a result of increased siltation. The gravel road approaches to both crossings were steep and showed evidence of erosion. Although there were no noticeable differences in turbidity above and below the crossings during normal summer flows,

TABLE 7.—Intrastream comparisons of length and weight at age of Atlantic salmon in logging-disturbed and control areas of five experimental streams. Asterisks indicate the control value is significantly different from the disturbed-area value: *$P < 0.05$; **$P < 0.01$.

Stream	Age	Disturbed mean±SD (N)	Control mean±SD (N)
		Fork length (mm)	
Renous	0+	48.7±4.3 (332)	49.3±4.2 (369)
	1+	86.4±6.4 (59)	84.1±7.0 (87)
	2+	118.0±6.4 (24)	116.9±6.3 (30)
Otter	0+	56.1±4.5 (393)	55.6±4.0 (445)
Bentley	0+	46.6±2.8 (137)	41.2±3.8 (235)**
McDonald	0+	51.3±3.3 (176)	49.4±3.1 (169)**
Thompson	0+	43.5±3.5 (363)	42.2±3.3 (223)**
	1+	76.4±5.0 (86)	73.6±6.2 (115)**
		Weight (g)	
Renous	0+	1.35±0.38 (97)	1.42±0.33 (78)
	1+	7.41±1.83 (23)	8.41±3.29 (28)
	2+	21.01±2.77 (8)	19.14±3.51 (10)
Otter	0+	2.04±0.44 (88)	1.88±0.44 (103)*
Bentley	0+	1.12±0.20 (67)	0.76±0.20 (94)**
McDonald	0+	1.53±0.29 (92)	1.44±0.26 (97)*
Thompson	0+	0.89±0.23 (78)	0.86±0.29 (61)
	1+	5.19±1.41 (30)	4.80±1.28 (38)

turbidity undoubtedly increases below these point sources after heavy rain. Even short-term increases in turbidity can decrease the standing crop of fish (Barton 1977).

Fine sediments have a more serious long-term effect when they settle out in the substrate, filling interstitial spaces, destroying the habitat of fish food organisms, and smothering spawning beds (Phillips et al. 1975; Hausle and Coble 1976; Moring 1982). It was noteworthy that the Stewiacke River crossing, although 9 years old and unused since 1977, still appeared to have a significant negative impact on the salmonid standing crop. The continuing impact probably occurs because revegetation was slow on the steep, unstable substrate of the gullies at the crossing.

The bank modification at Lower Otter Brook and the seven clear-cuts had no significant effect on total salmonid biomass. The two major negative impacts of clear-cutting—increased water temperature and sedimentation (Gibbons and Salo 1973; Lynch et al. 1977)—were not evident in the disturbed areas. This may have been due to the small size of the cutover areas, which minimized road construction, skidding, and the percentage of the stream exposed to direct sunlight.

Clear-cutting can have positive impacts. Reducing the canopy cover often increases salmonid biomass by increasing primary production and the standing crop of macroinvertebrates (Chapman and Knudsen 1980; Murphy and Hall 1981; Murphy et al. 1981). However, these authors stressed that increases in salmonid biomass only occur when the positive effects of increased productivity outweigh the negative effects of increased sediment load. Clear-cut logging in some Cascade Mountain watersheds did not lead to significant accumulations of sediment because stream gradient, substrate resistance to erosion, and the capacity to flush out sediments during spates were generally high (Murphy and Hall 1981; Murphy et al. 1981). Our study streams generally had lower gradients, more erosive substrates, and presumably smaller spates than those in the Cascade Mountains. Therefore, the adverse effects of sedimentation were potentially more severe and may have balanced any positive effects of increased productivity.

There was no increase in salmonid standing crop, but there was indirect evidence that removal of the canopy cover increased productivity. The percentage of the substrate covered by periphyton, which was quantified in two streams, was greater in the disturbed areas of McDonald Brook (disturbed = 65%, control = 25%; $P < 0.01$) and Thompson Brook (disturbed = 66%, control = 31%; $P < 0.05$). Also, fork length or weight at age, or both, of juvenile Atlantic salmon increased in all disturbed areas where percent canopy cover was reduced (Table 7). However, we must be careful in relating size at age to reduction in canopy cover because size also varied significantly in two of three control streams. Nevertheless, the consistent increase in either fork length or weight of juvenile Atlantic salmon suggested that increased sunlight was the causal factor.

Reduction in canopy cover had no effect on the size at age of brook trout in this study, perhaps because brook trout used habitat differently from Atlantic salmon. Brook trout predominate in slower, deeper water with overhanging cover (Hunt 1969; Gibson 1978; Power 1980), while Atlantic salmon predominate in open, fast riffles (Symons and Heland 1978). Riffle species tend to benefit from the increase in productivity associated with clear-cutting, whereas pool species tend to be negatively affected by the accumulation of fine sediments in slow water and the removal of overhanging vegetation (Chapman and Knudsen 1980; Murphy and Hall 1981).

Acknowledgments

This study was funded by Supply and Services Canada, Environment Canada, and Fisheries and Oceans Canada. We thank A. Ducharme, F. Meth, J. Martin, D. Morantz, and R. Wilson for advice concerning site selection and field methods. J. D. Irving, Limited, the Miramichi Lumber Company (Limited), Scott Paper International, Incorporated, the Nova Scotia Department of Lands and Forests, and the New Brunswick Department of Natural Resources kindly provided cutting maps and access to their property. D. Morantz, D. Noakes, R. Wilson, and two anonymous reviewers read and improved an earlier draft of this paper.

References

Adams, N. N., and R. L. Beschta. 1980. Gravel bed composition in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences 37:1514–1521.

Barton, B. A. 1977. Short-term effects of highway construction on the limnology of a small stream in southern Ontario. Freshwater Biology 7:99–108.

Beschta, R. L. 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14:1011–1016.

Booke, H. E., B. Hollender, and G. Lutterbie. 1978. Sodium bicarbonate, an inexpensive fish anaesthetic for field use. Progressive Fish-Culturist 40:11–13.

Brown, G. W., and J. T. Krygier. 1970. Effects of clear-cutting on stream temperature. Water Resources Research 6:1133–1139.

Brown, G. W., and J. T. Krygier. 1971. Clear-cut logging and sediment production in the Oregon Coast Range. Water Resources Research 7:1189–1198.

Burns, J. W. 1970. Spawning bed sedimentation studies in northern California streams. California Fish and Game 56:253–270.

Burns, J. W. 1972. Some effects of logging and associated road construction on northern California streams. Transactions of the American Fisheries Society 101:1–17.

Chapman, D. W., and E. Knudsen. 1980. Channelization and livestock impacts on salmonid habitat and biomass in western Washington. Transactions of the American Fisheries Society 109:357–363.

Fausch, K. D., and R. J. White. 1981. Competition between brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) for positions in a Michigan stream. Canadian Journal of Fisheries and Aquatic Sciences 38:1220–1227.

Gibbons, D. R., and E. O. Salo. 1973. An annotated bibliography of the effects of logging on fish of the western United States and Canada. U.S. Forest Service General Technical Report PNW-10.

Gibson, R. J. 1978. The behavior of juvenile Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) with regard to temperature and to water velocity. Transactions of the American Fisheries Society 107:703–712.

Green, R. H. 1979. Sampling design and statistical methods for environmental biologists. John Wiley and Sons, New York.

Hall, J. D., and R. L. Lantz. 1969. Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. Pages 355–375 *in* T. G. Northcote, editor. Symposium on salmon and trout in streams. University of British Columbia, Vancouver.

Hall, J. D., M. L. Murphy, and R. S. Aho. 1978. An improved design for assessing impacts of watershed practices on small streams. Internationale Vereinigung fuer Theoretische und Angewandte Limnologie Verhandlungen 20:1359–1365.

Harr, R. D., and F. M. McCorison. 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon. Water Resources Research 15:90–94.

Hausle, D. A., and D. W. Coble. 1976. Influence of sand in redds on survival and emergence of brook trout (*Salvelinus fontinalis*). Transactions of the American Fisheries Society 105:57–63.

Hunt, R. L. 1969. Effects of habitat alteration on production, standing crop and yield of brook trout in Lawrence Creek, Wisconsin. Pages 281–312 *in* T. G. Northcote, editor. Symposium on salmon and trout in streams. University of British Columbia, Vancouver.

Hynes, H. B. N. 1970. The ecology of running waters. University of Toronto Press, Toronto.

Kalleberg, H. 1958. Observations in a stream tank of territoriality and competition in juvenile salmon and trout (*Salmo salar* L. and *Salmo trutta* L.). Institute of Freshwater Research, Drottningham Report 39.

Krause, H. H., and H. B. King. 1981. Effect of clear-cutting on streamwater quality. Pages 19–21 *in* G. R. Powell, editor. Nashwaak experimental watershed project. New Brunswick Department of Natural Resources, Fredericton.

Lynch, J. A., E. S. Corbett, and R. Hoopes. 1977. Implications of forest management practices on the aquatic environment. Fisheries (Bethesda) 2(2):16–22.

Moring, J. R. 1975. The Alsea Watershed Study: effects of logging on the aquatic resources of three headwater streams of Alsea River, Oregon. Oregon Department of Fisheries, Research Report 9, Portland.

Moring, J. R. 1982. Decrease in stream gravel permeability after clear-cut logging: an indication of intragravel conditions for developing salmonid eggs and alevins. Hydrobiologia 88:295–298.

Murphy, M. L., and J. D. Hall. 1981. Varied effects of clear-cut logging on predators and their habitat in small streams of the Cascade Mountains, Oregon. Canadian Journal of Fisheries and Aquatic Sciences 38:137–145.

Murphy, M. L., C. P. Hawkins, and N. H. Anderson. 1981. Effects of canopy modification and accumulated sediment on stream communities. Transactions of the American Fisheries Society 110:469–478.

Phillips, R. W., R. L. Lantz, E. W. Claire, and J. R. Moring. 1975. Some effects of gravel mixture on emergence of coho salmon and steelhead trout fry. Transactions of the American Fisheries Society 104: 461–466.

Power, G. 1980. The brook charr, *Salvelinus fontinalis*. Pages 141–203 *in* E. K. Balon, editor. Charrs: salmonid fishes of the genus *Salvelinus*. Dr. W. Junk, The Hague.

Scott, W. B., and E. J. Crossman. 1973. Freshwater fishes of Canada. Fisheries Research Board of Canada Bulletin 184.

Scrivener, J. C., and M. J. Brownlee. 1981. A preliminary analysis of Carnation Creek gravel quality data, 1973–1980. Pages 195–226 *in* Proceedings of salmon-spawning gravel, a renewable resource in the Pacific Northwest? Washington State University, Water Research Center, Pullman.

Symons, P. E. K., and M. Heland. 1978. Stream habitats and behavioural interactions of underyearling and yearling Atlantic salmon (*Salmo salar*). Journal of the Fisheries Research Board of Canada 35:174–183.

Tschaplinski, P. J., and G. F. Hartman. 1983. Winter distribution of juvenile coho salmon (*Oncorhynchus kisutch*) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Canadian Journal of Fisheries and Aquatic Sciences 40:452–461.