

# Effects of Clear-cut Logging with and without Buffer Strips on Juvenile Salmonids in Alaskan Streams<sup>1</sup>

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To assess short-term effects of logging on juvenile *Oncorhynchus kisutch*, *Salvelinus malma*, *Salmo gairdneri*, and *Salmo clarki* in southeastern Alaska, we compared fish density and habitat in summer and winter in 18 streams in old-growth forest and in clearcuts with and without buffer strips. Buffered reaches did not consistently differ from old-growth reaches; clear-cut reaches had more periphyton, lower channel stability, and less canopy, pool volume, large woody debris, and undercut banks than old-growth reaches. In summer, if areas had underlying limestone, clear-cut reaches and buffered reaches with open canopy had more periphyton, benthos, and coho salmon fry (age 0) than old-growth reaches. In winter, abundance of parr (age >0) depended on amount of debris. If debris was left in clear-cut reaches, or added in buffered reaches, coho salmon parr were abundant (10-22/100 m<sup>2</sup>). If debris had been removed from clear-cut reaches, parr were scarce (<2/100 m<sup>2</sup>). Thus, clear-cutting may increase fry abundance in summer in some streams by increasing primary production, but may reduce abundance of parr in winter if debris is removed. Use of buffer strips maintains or increases debris, protects habitat, allows increased primary production, and can increase abundance of fry and parr.

Afin d'évaluer les effets à courte échéance du déboisement sur les formes juvéniles d'*Oncorhynchus kisutch*, de *Salvelinus malma*, de *Salmo gairdneri* et de *Salmo clarki* du sud-est de l'Alaska, nous avons comparé la densité de population ainsi que l'habitat de ces poissons tant en été qu'en hiver dans 18 cours d'eau de régions boisées et de régions déboisées, avec et sans bandes-tampons. Les régions tamponnées n'ont pas été trouvées constamment différentes des régions boisées; par ailleurs, les régions déboisées possédaient plus de périphyton, un lit moins stable, un couvert de verdure moins fourni, des bassins de moindre volume, moins de gros branchages et de rives affouillées que les régions comparables dans les boisés. Pendant l'été, dans les régions à fonds calcaires, les surfaces tant déboisées que tamponnées avec couvert dégarni comportaient plus de périphyton, de benthos et d'alevins de saumon coho (âge 0) que les régions boisées. En hiver, l'abondance des tacons (âge >0) dépendait de la quantité de débris. Lorsque les parties droites des cours d'eau des régions déboisées comportaient des débris, ou s'il en avait été ajouté dans les régions tamponnées, les tacons de saumon coho abondaient (10-22/100 m<sup>2</sup>). Lorsque les débris avaient été retirés des cours rectilignes dans les régions déboisées, les tacons se faisaient rares (<2/100 m<sup>2</sup>). Le déboisement peut donc augmenter l'abondance des alevins en été dans certains cours d'eau en favorisant la production primaire mais il risque de diminuer l'abondance des tacons en hiver si les débris ont disparu. La création de bandes-tampons conserve ou augmente les débris, protège l'habitat, favorise la production primaire et peut augmenter l'abondance des alevins et des tacons.

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Southeastern Alaska has the most extensive old-growth forest remaining in the United States. About 1.4 million ha of this forest, mainly western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea sitchensis*), is commercial quality available for harvest, and about 8100 ha (0.6%) is harvested annually (Lentfer et al. 1980). Clear-cutting is the most common method of timber harvest, and trees are usually cut to the stream bank. To protect fish habitat, trees are normally felled away from streams and suspended when yarded across streams. Strips of uncut, streamside trees (buffer strips) are seldom left to protect fish habitat because the exposed trees may blow down.

Commercial and sport fisheries are a major contribution to the region's economy. Southeastern Alaska annually produces about 20 million Pacific salmon (*Oncorhynchus* spp.), worth over \$100 million. All five species of Pacific salmon occur in southeastern Alaska, as well as steelhead trout (*Salmo gairdneri*), cutthroat trout (*S. clarki*), and Dolly Varden (*Salvelinus malma*).

Logging can be either beneficial or detrimental to fish, depending on the extent of changes in habitat and the species or life stage affected. Juvenile salmonids can be more abundant in recently logged areas (<15 yr old) than in nearby forested areas. Increased light reaching the stream after canopy removal can stimulate aquatic primary and secondary production (Murphy and Hall 1981; Bisson and Sedell 1984). Fish growth may also be enhanced after logging by warmer stream temperature which accelerates emergence and extends the growing

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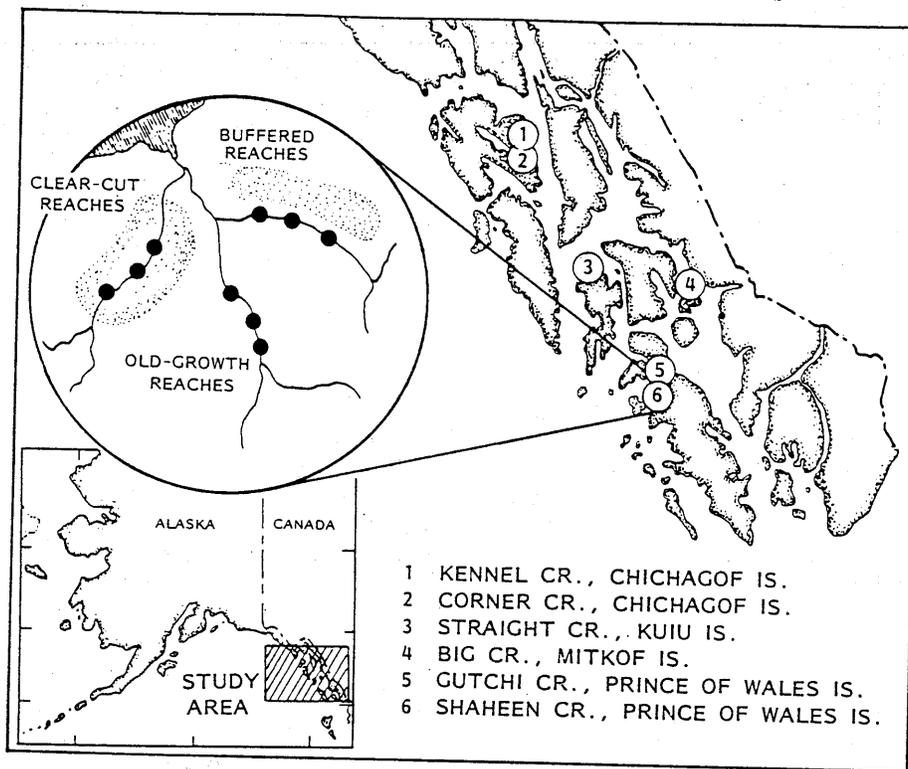


FIG. 1. Location of the study sites in southeastern Alaska and an example of a block, treatments, and study reaches (solid circles). The creeks listed are the major streams in each block (Big Creek is also informally known as Bear Creek). Treatment reaches were usually located on unnamed tributaries of these streams or in adjacent watersheds.

season (Holtby and Hartman 1982; Scrivener and Andersen 1984).

On the other hand, salmonid populations may decline after logging because of detrimental changes in physical habitat. These changes include excessive sedimentation (Platts and Megahan 1975; Scrivener and Brownlee 1982), less dissolved oxygen and elevated temperature (Ringler and Hall 1975), loss of large woody debris, collapsed stream banks, and decreased channel stability (Tschaplinski and Hartman 1983; Bisson and Sedell 1984). Features of fish habitat that need protection during logging must be identified so that timber can be harvested without damaging fish habitat yet allowing the benefits of increased primary and secondary production and extended growing season.

Most studies of effects of logging in the Pacific Northwest and British Columbia have limited application in Alaska where logging practices, climate, geomorphology, and vegetation are different. For example, high-lead yarding is the most common logging practice in Alaska, whereas a variety of yarding methods, including skyline yarding, are used in Oregon and Washington. The cool Alaskan climate may eliminate the need to protect most streams from excessive temperature increases after logging, increases which in Oregon can kill salmonids (Moring and Lantz 1975). Buffer strips protect fish habitat in western Oregon and northern California (Hall and Lantz 1969; Newbold et al. 1980), but in Alaska, the effectiveness of buffer strips is uncertain.

Objectives of this paper are to assess short-term (<15 yr) effects of clear-cut logging, with and without buffer strips, on density of juvenile salmonids that rear in streams in southeastern Alaska and to identify habitat features that mediate these effects. To assess the effects of logging, we compare fish

densities and habitat in old-growth and logged areas. We then relate fish density to habitat to identify habitat features that account for effects of logging and the importance of buffer strips.

## Methods

### Experimental Design

This study was based on an extensive posttreatment comparison (Hall et al. 1978) of fish densities and habitat in stream reaches with three types of treatments (Fig. 1): undisturbed forest (old-growth), clearcuts with streamside buffer strips (buffered), and clearcuts without buffer strips (clear-cut). Study streams were selected to fit a randomized, complete block design. A block consisted of a set of three streams, one of each treatment, preferably in the same watershed. The stream in each treatment area was divided into three sections of equal length, and one 30-m study reach was randomly selected from each section.

Six blocks were selected to cover regional variation in southeastern Alaska: two northern blocks on Chichagof Island, two central blocks on Kuiu and Mitkof Islands, and two southern blocks on Prince of Wales Island (Fig. 1). All three treatments, however, were usually not present in the same watershed, and five of the six blocks were composed of adjacent watersheds. All six blocks were sampled once in summer (June–August 1982) for fish and habitat, and all except Mitkof Island were sampled again for fish in winter (February–March 1983).

### Characteristics of the Streams

The study streams were second to fourth order (Strahler

1957), had a low-flow discharge of 0.01–0.3 m<sup>3</sup>/s, and had a channel gradient of 0.1–3.0%. Maximum water temperature recorded periodically in summer ranged from about 13 to 17°C in the northern and southern streams, respectively. Winter temperature ranged from 0 to 2°C. Streambed substrate consisted mostly of gravel and small cobble. Most streams had juvenile coho salmon (*Oncorhynchus kisutch*) and Dolly Varden, which were usually the most abundant fishes. About half the streams also had juvenile steelhead trout or cutthroat trout. Although common, sculpins (*Cottus aleuticus* and *C. asper*) were omitted from our analyses.

Old-growth reaches were, in all cases, located in mature forests of western hemlock and Sitka spruce, and none had any logging upstream. Buffered reaches were on the edge of 3- to 10-yr-old clearcuts: one bank had a strip of uncut streamside trees; the other had undisturbed forest (Fig. 1). In some, a logging road abutted the buffer strip, or a bridge crossed the stream. Buffer strips were 15–130 m wide and 300–600 m long, and some were selectively logged. About half the buffered reaches had one or two trees that had apparently fallen into the stream after logging. Several buffered reaches had more blowdown, and along one reach in the Shaheen Creek block, the buffer strip had mostly blown down. The clear-cut reaches flowed through 1- to 12-yr-old clearcuts where trees had been cut to both stream banks (Fig. 1). The one exception, clear-cut reaches in the Big Creek block, Mitkof Island, had undisturbed forest along one bank.

#### Habitat Measurements

We quantified key habitat features that may affect densities of juvenile salmonids: stream size and gradient, sediment, forest canopy, undercut banks, channel stability, pool volume, and volume of large woody debris. We also assessed primary and secondary production by measuring standing crops of periphyton and benthos. Johnson and Heifetz (1985) give details of our methods.

Habitat features at each reach were measured once in summer. We estimated stream discharge by measuring cross-sectional area and water velocity across a uniform glide. Channel gradient was measured with a hand-held level and stadia rod. At 3-m intervals along the reach, we measured stream width and estimated amount of fine sediment (<2 mm) by measuring the distance it covered across these transects. We used a hand-held convex mirror (Lemmon 1956) to estimate canopy density over the middle of the stream. Area of undercut banks was computed by multiplying length of undercut by average width of overhang. We assessed channel stability with Pfankuch's (1975) index. Pool volume was calculated by the formula for a rectangular solid from measurements of length, width, and depth of each pool. Total pool volume was standardized by dividing it by stream area.

All pieces of large woody debris (>10 cm diameter and >1 m long) within the annual high-water level of the channel were measured. The portion of each piece submerged or floating in the stream was visually estimated. Volume of boles was calculated by the Smalian formula (Chapman and Meyer 1949), and volume of root wads was calculated by the formula for a frustum. Volume of instream debris was standardized by dividing it by stream area.

Periphyton biomass per unit area of stream bed substrate was estimated from four samples of single cobbles (10–30 cm diameter) randomly selected from riffles. Attached periphyton was scrubbed from the cobbles into 50-mL jars and preserved

in 5% formaldehyde. In the laboratory, the supernatant was decanted after the periphyton settled, and samples were dried (48 h, 60°C) and ashed (4 h, 550°C) to determine ash-free dry matter. To determine surface area of the cobbles, we measured three orthogonal axes of each cobble and calculated surface area by the formula for a rectangular solid. Because periphyton was concentrated on the exposed, upper half of the cobbles, only one half of total surface was used as the reference area for biomass.

In each reach, density of benthic invertebrates was estimated from four samples randomly selected from riffles. A modified Hess sampler (area 170 cm<sup>2</sup>) was forced into the stream bed, and sediment to a depth of 10 cm was excavated into a bucket. The sample was then agitated with water, and invertebrates were decanted onto a 280- $\mu$ m-mesh net and combined with those from a 280- $\mu$ m-mesh net attached to the sampler. Invertebrates were preserved in 10% formaldehyde and later counted under a microscope.

#### Salmonid Populations

Populations of all salmonids in each reach were estimated by single-census mark and recapture (Robson and Regier 1971). We enclosed fish within each reach by blocking both ends with seines. Fish were collected with seines, electroshockers, and traps baited with salmon roe (Bloom 1976). Captured fish were anesthetized with dilute Tricaine solution, identified, measured, weighed, and marked by removal of a tip of the caudal fin. After the fish recovered from anesthesia, they were released in the same area as captured. Following the practice of Peterson and Cederholm (1984), we waited at least 1 h before attempting recapture.

Population estimates were calculated separately for fry (age 0) and parr (age >0), which were separated primarily on the basis of length. Coho fry, for example, ranged from 31 to 71 mm in summer, compared with 45 to 117 mm for coho parr. To help separate coho salmon fry from parr from streams where their sizes overlapped, we took scales from about 30 coho salmon whose lengths spanned the region of length overlap, determined age from the scales, and divided 5-mm size classes of salmon proportionately. Fish density was standardized by dividing population estimates by the area of stream in summer.

Following guidelines in Robson and Regier (1971), we tried to mark ( $M$ ), recapture ( $R$ ), and examine for marks ( $C$ ) enough fish so that population estimates ( $\hat{N}$ ) would not depart from the true population size by more than 25%, 95% of the time. This level of precision, however, was difficult to achieve in practice because many populations were small, and some species and age-classes were difficult to capture. The average 95% confidence interval for 320 estimates of coho salmon fry and parr, Dolly Varden parr, and trout parr populations in summer and winter (estimates with  $M = 0$  or  $C = 0$  omitted) was  $\hat{N} \pm 58\%$ .

We only considered data for coho salmon fry and parr, Dolly Varden parr, and trout parr (steelhead and cutthroat trout combined). Dolly Varden fry and trout fry emerged late and were difficult to capture; hence, few estimates of their populations were reliable. Total density of salmonid parr was strongly correlated with density of Dolly Varden parr in both summer ( $r = 0.95$ ,  $n = 54$ ) and winter ( $r = 0.95$ ,  $n = 45$ ) and therefore was excluded from the analysis.

#### Data Analysis

The data analysis was divided into two parts with different

TABLE 1. Habitat variables included in the regression analysis.

Habitat variable	Definition
Stream width (m)	Mean stream width
Channel gradient (%)	Percent change in elevation of reach, from bottom to top, relative to reach length
Fine sediment (%)	Percent of lateral-transect length that covered sediment <2 mm diameter
Channel instability (nondimensional)	Pfankuch (1975) index, high values indicate low stability
Undercut banks (m <sup>2</sup> )	Total area of undercut bank
Canopy density (%)	Percent canopy closure, based on method of Lemmon (1956)
Pool volume (m <sup>3</sup> /100 m <sup>2</sup> )	Volume of pools per 100 m <sup>2</sup> of stream area
Instream debris (m <sup>3</sup> /100 m <sup>2</sup> )	Volume of instream large woody debris per 100 m <sup>2</sup> of stream area
Periphyton biomass (mg AFDM/m <sup>2</sup> )	Mean ash-free dry weight of periphyton per square metre of stream bed in riffles
Benthos density (thousands/m <sup>2</sup> )	Mean no. of benthic macroinvertebrates per square metre of stream bed in riffles

TABLE 2. Number of reaches with reliable population estimates by block and treatment in summer (S) and winter (W) that were included in the regression analysis. Population estimates in these reaches had at least one fish marked and released ( $M > 0$ ) and at least 15% marked fish in the recapture sample ( $R/C > 0.15$ ).

	Coho salmon				Dolly Varden parr		Trout parr	
	Fry		Parr		S	W	S	W
	S	W	S	W				
<i>Block</i>								
Chichagof Island								
Kennel Creek	5	7	6	6	8	6	3	6
Corner Creek	6	5	9	8	6	4	8	8
Kuiu Island								
Straight Creek	0	4	9	4	5	4	0	0
Prince of Wales Island								
Gutchi Creek	6	7	7	7	5	6	7	6
Shaheen Creek	8	9	9	9	7	8	7	6
<i>Treatment</i>								
Old-growth	7	11	12	12	9	10	12	11
Buffered	9	12	14	9	9	7	5	6
Clear-cut	9	9	14	13	13	11	8	9
Total	25	32	40	34	31	28	25	26

objectives. First, to detect effects of logging on fish density and habitat, we used analysis of variance (ANOVA), with treatment, block, and region (southern, central, and northern) as factors. Second, to identify possible causes of treatment effects on fish, we used multiple regression analysis to examine associations between fish density and habitat.

The ANOVA was based on a mixed model, with random block effects, fixed treatment and region effects, and with repeated observations on streams (Winer 1971) in their lower, middle, and upper sections. Within-stream means and standard deviations for each variable were examined to determine if the variance was associated with the mean. If so, data were transformed to square roots or logarithms based on the slope of the regression of the logarithm of the standard deviation on the logarithm of the mean (Dixon et al. 1983). We transformed data for fish densities, stream gradient, sediment, undercut bank area, pool volume, debris volume, and periphyton biomass to square roots and transformed stream width and benthos density to logarithms. Planned a priori *t*-tests were used to compare the old-growth treatment with the buffered and clear-

cut treatments. We included data from all reaches, regardless of precision of population estimates, to avoid any bias in data selection. For winter fish densities, however, only one central block, Kuiu Island, was sampled; therefore, we excluded data from this block to balance the design for the ANOVA.

In the multiple regression, we regressed fish density on 10 habitat variables (Table 1) by forward step-wise procedure (Kim and Kohout 1975) until all significant ( $P < 0.05$ ) variables were added. Regression models that included data from all reaches often explained little of observed variation in fish density and had low coefficients of determination ( $R^2 < 0.3$ ). To more reasonably evaluate the regression models, we included only those population estimates with good reliability:  $M > 0$  and  $R/C > 0.15$  (Table 2). For example, the Big Creek block, Mitkof Island, was deleted because the electroshocker malfunctioned and population estimates were unreliable. In summer, some streams were sampled before most coho salmon fry had emerged, which added excessive variance and made the regression analysis inconclusive. Therefore, in the regression analysis of summer fry density, we included only data from reaches where mean length of fry was  $>40$  mm. The number of reaches used in the analysis ranged from 25 to 40 for summer coho salmon fry and parr, respectively (Table 2). Reaches were well distributed among the five blocks and the three logging treatments, except there were few buffered reaches with trout parr.

## Results and Discussion

Fish densities and habitat often differed significantly between the old-growth, buffered, and clear-cut reaches, but treatment effects were frequently inconsistent among blocks. Such inconsistency probably resulted from variable stream characteristics and logging practices among the six study locations. The treatment  $\times$  region interaction was nearly significant at  $P < 0.15$  for periphyton biomass, summer density of coho salmon fry, and winter density of coho salmon parr. For these, treatments tended to have different effects in the southern, central, and northern regions. Treatment effects on all other variables were similar in the three regions.

### Effects on Habitat

Although treatments were similar in stream width, channel gradient, and percentage of fine sediment, clear-cut reaches had less undercut bank, canopy density, pool volume, and debris and more periphyton than old-growth reaches (Table 3). Clear-cut reaches were also less stable than old-growth reaches, having significantly greater point-bar formation, sedi-

TABLE 3. Comparison of habitat in old-growth, buffered, and clear-cut reaches. Data are means of habitat variables measured in 18 reaches of 6 streams for each treatment (95% confidence intervals are in parentheses). Significance is based on a mixed-model analysis of variance, with fixed treatment and region effects and random block effects, as explained in Methods. Asterisks show results of a priori *t*-tests: treatment different from old growth. \* $P < 0.10$ ; \*\* $P < 0.05$ ; \*\*\* $P < 0.01$ .

Habitat variable	Old-growth	Buffered	Clear-cut	Treatment × region interaction <i>P</i>	Treatment effect <i>P</i>
Stream width (m)	5.8 (3.9–8.5)	7.0 (4.8–10.2)	4.9 (3.3–7.2)	0.39	0.35
Channel gradient (%)	1.3 (0.9–1.7)	1.2 (0.9–1.7)	1.2 (0.8–1.6)	0.28	0.88
Fine sediment (%)	7.9 (3.1–14.8)	11.2 (5.2–19.2)	7.8 (3.0–14.7)	0.79	0.61
Channel instability	68.9 (61.5–76.3)	75.5 (68.1–76.3)	91.9*** (84.5–99.2)	0.33	0.004
Undercut banks (m <sup>2</sup> )	6.0 (4.7–9.5)	4.2 (2.9–7.7)	2.2** (0.6–5.4)	0.81	0.08
Canopy density (%)	73.8 (61.2–86.4)	64.6 (51.9–77.2)	26.7*** (14.1–39.3)	0.40	0.002
Pool volume (m <sup>3</sup> /100 m <sup>2</sup> )	21.4 (17.3–26.0)	16.6 (13.0–20.6)	9.4*** (6.7–12.5)	0.34	0.003
Instream debris (m <sup>3</sup> /100 m <sup>2</sup> )	2.2 (1.1–3.6)	4.0* (2.5–5.9)	1.0* (0.4–2.0)	0.28	0.02
Periphyton biomass (mg AFDM/m <sup>2</sup> )	2.0 (1.2–3.2)	2.9 (1.8–4.7)	4.6** (2.9–7.4)	0.14	0.06
Benthos density (thousands/m <sup>2</sup> )	5.0 (2.6–9.6)	7.8 (4.1–15.1)	7.9 (4.1–15.5)	0.32	0.43

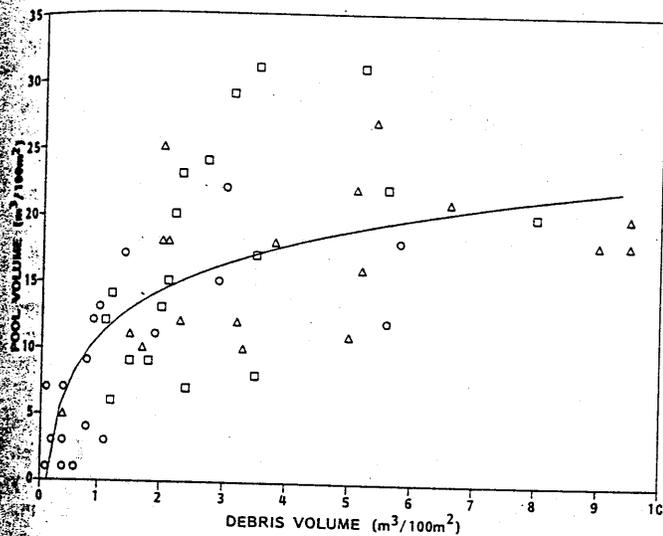


FIG. 2. Relationship between pool volume and debris volume in the old-growth (□), buffered (△), and clear-cut (○) reaches. The regression equation was pool volume = 10.8 + 5.0 ln (debris volume);  $R^2 = 0.47$ ,  $n = 54$  reaches,  $P < 0.001$ .

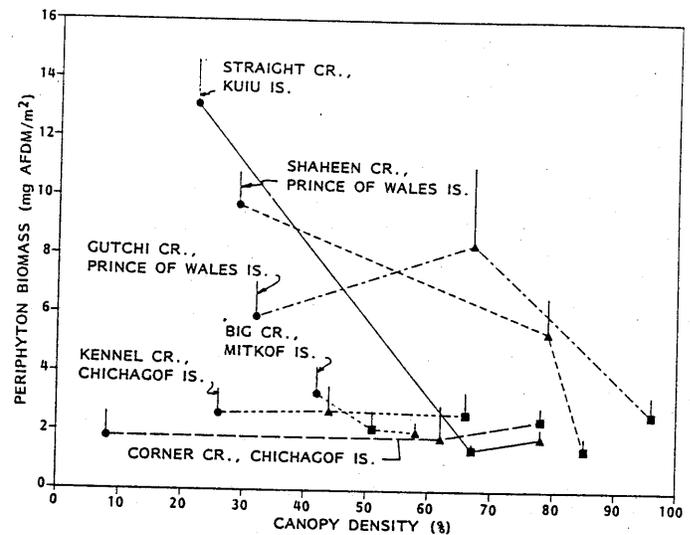


FIG. 3. Relationships between periphyton biomass and canopy density in the old-growth (□), buffered (△), and clear-cut (○) reaches in each of the six blocks. Points are means; bars are upper halves of 95% confidence intervals for periphyton biomass. As in Fig. 1, stream names refer to the major streams in each block.

ment packing, and scour and deposition. Buffered reaches, on the other hand, had more debris than old-growth reaches but did not differ consistently from old-growth reaches in any other habitat variable.

Compared with that in old growth, debris volume was greater in buffered reaches but less in clear-cut reaches (Table 3; Fig. 2). Although buffered reaches averaged 82% more debris than old-growth reaches, this difference was mainly due to blowdown in only a few reaches. Clear-cut reaches averaged 54% less debris than old-growth reaches, but debris volume varied. Some clear-cut reaches had apparently been overcleaned of debris after logging; natural as well as logging debris had been removed, and debris was virtually absent. In a few reaches, however, much natural debris remained, and debris was as abundant as in old growth. Because of the variability in treatment effects, the differences in debris volume between logged and old-growth reaches were only mildly significant ( $P < 0.10$ , *t*-test).

Most pools were formed by debris, and pool volume and debris volume were directly related (Fig. 2). The few buffered

reaches with heavy blowdown had the most debris, but pool volume, although large, was similar to that in some old-growth reaches with less debris. The new debris from blowdown had probably not yet produced an increase in pool volume. Clear-cut reaches had less debris than old-growth reaches, and as a result, averaged 56% less pool volume (Table 3). Where natural debris was left, however, pool volume was maintained.

Canopy density depended on logging treatment (Fig. 3). Clear-cutting to both stream banks reduced canopy to an average density of 8–32%, and clear-cutting to one bank only (Big Creek block, Mitkof Island) reduced canopy density to 42%. Buffers had variable effects on canopy, depending on buffer width. For example, in the central blocks on Kuiu and Mitkof islands, buffer strips were >100 m wide, and canopy density was greater over these buffered reaches than over comparable reaches in old growth. All other buffers were narrower (mean 45 m), selectively logged, or partially blown down, and they provided less canopy than did comparable old growth.

Periphyton biomass averaged 130% greater in clear-cut

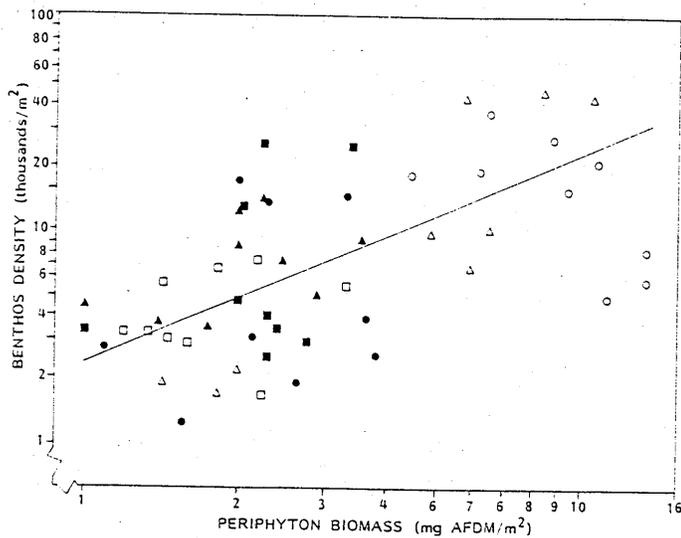


FIG. 4. Relationship between benthos density and periphyton biomass in the old-growth ( $\square$ ,  $\blacksquare$ ), buffered ( $\triangle$ ,  $\blacktriangle$ ), and clear-cut reaches ( $\circ$ ,  $\bullet$ ). Open symbols indicate data from Kuiu and Prince of Wales islands. Points are means of four samples of both periphyton biomass and benthos density from each reach. Both axes are in logarithmic scale. The regression equation was  $\log(\text{benthos}) = 0.76 \log(\text{periphyton}) + 0.46$ ;  $R^2 = 0.34$ ,  $n = 54$  reaches,  $P < 0.001$ .

reaches than in old-growth reaches, but the treatment effect varied among the three regions (Table 3; Fig. 3). In the four southern and central blocks on Kuiu, Mitkof, and Prince of Wales islands, canopy removal appeared to increase abundance of periphyton, probably by increasing the amount of light reaching the stream (Murphy and Hall 1981). In these blocks, differences in periphyton roughly corresponded to differences in canopy. In the two northern blocks on Chichagof Island, however, periphyton biomass was unrelated to canopy; the clear-cut reaches had sparse periphyton even though they were exposed to direct sunlight.

The difference in periphyton biomass between old-growth and buffered reaches was not significant because of variation in the buffered treatment's effect on canopy density and differences among regions (Table 3; Fig. 3). The wide buffers in the central blocks on Kuiu and Mitkof islands provided as much canopy as old growth, and these buffered reaches had sparse periphyton. The buffered reaches in the southern blocks on Prince of Wales Island were more open to sunlight and had abundant periphyton. As with clear-cut reaches on Chichagof Island, the buffered reaches there had sparse periphyton even though their canopies averaged 66 and 80% of that in comparable old growth.

Periphyton biomass and benthos density were directly related (Fig. 4). The clear-cut and buffered reaches with open canopy and abundant periphyton also had abundant benthos, whereas the reaches with sparse periphyton, whether logged or old growth, generally had sparse benthos. The relationship was clearest among the reaches on Kuiu and Prince of Wales islands. Increased biomass of periphyton apparently led to high benthos density via energy transfer through the food web (Hawkins et al. 1982).

As with periphyton biomass, benthos density was usually greater (depending on canopy) in buffered and clear-cut reaches than in old-growth reaches in the southern and central blocks, but density was similar among treatments in the northern blocks. The treatment effect and treatment  $\times$  region inter-

action, however, were not significant when all three treatments were compared in the ANOVA (Table 3) because of variation in the buffered treatment, i.e. variation in buffer width masked any treatment effect. A separate ANOVA of only old-growth and clear-cut treatments showed a significant treatment effect ( $P = 0.06$ ) and treatment  $\times$  region interaction ( $P = 0.03$ ). Thus, in the southern and central regions, clear-cut reaches averaged significantly more benthos than did old-growth reaches ( $10\,046/\text{m}^2$  in clearcuts vs.  $4\,111/\text{m}^2$  in old growth), but in the north, there was no effect ( $5\,370/\text{m}^2$  in clearcuts vs.  $8\,511/\text{m}^2$  in old growth).

#### Coho Salmon Fry

Summer density of coho salmon fry averaged more than two times greater in both buffered and clear-cut reaches than in old-growth reaches, but treatment effects differed among regions (Table 4; Fig. 5). As with periphyton biomass, fry density was greater in clear-cut than in old-growth reaches in the four southern and central blocks on Kuiu, Mitkof, and Prince of Wales islands, but densities were similar in clear-cut and old-growth reaches in the two northern blocks on Chichagof Island. Buffered reaches had more fry than old-growth reaches in the two southern blocks and in one northern block, Corner Creek, where they had a high density of mostly small fry that had recently emerged. Reaches with wide buffers in the two central blocks were similar to old growth.

Logging effects on summer density of coho salmon fry were related to effects on periphyton and benthos. Summer fry density was directly related to periphyton biomass and benthos density, and best modeled by periphyton biomass (Table 5; Fig. 6). The more periphyton a reach had, the more fry it had, and the clear-cut and buffered reaches with open canopy and abundant periphyton had the most fry. The correlation between fry density and periphyton biomass was much higher for the 25 reaches with fry  $>40$  mm mean length than for all 54 reaches ( $r = 0.90$  vs.  $r = 0.37$ ). Apparently, the relationship between fry density and periphyton biomass was clearest where fry densities had the most time to adjust to the reaches' carrying capacities.

In winter, density of coho salmon fry was still greater in buffered than in old-growth reaches (Table 4). Clear-cut reaches, however, no longer had significantly more fry than old-growth reaches, and treatment effects no longer differed among regions. Differences between clear-cut and old-growth reaches changed in several blocks between summer and winter (Fig. 5). Fry density in clear-cut reaches was still greater than in old-growth reaches in only two blocks, Straight and Shaheen creeks, and was less than in old-growth reaches in the northern Corner Creek block.

Both summer food abundance and debris appeared to influence winter density of coho salmon fry. In winter, density of fry was still directly related to summer periphyton biomass and benthos density, although the correlations were not as strong as in summer (Table 5). Winter fry density was best modeled by a combination of summer periphyton biomass and volume of instream debris (Fig. 6). The more periphyton a reach had in summer and the more debris, the more fry it had in winter.

Apparently, summer food abundance limited summer fry densities, and quality of winter habitat (i.e. debris) determined winter survival. For example, fry density declined 98% (from  $1.4$  to  $0.03/\text{m}^2$ ) from summer to winter in two clear-cut reaches in the Gutchi Creek block, Prince of Wales Island, that had abundant periphyton and benthos in summer but contained

DENSITY OF COHO SALMON FRY (no./100 m<sup>2</sup>)

FIG. 5. clear-cut summer ranges do not Names

TABLE 4. Comparison of fish density (no./100 m<sup>2</sup>) in old-growth, buffered, and clear-cut reaches in summer and winter. Data are means of 18 reaches of 6 streams for each treatment in summer and 12 reaches of 4 streams for each treatment in winter (95% confidence intervals are in parentheses). Significance is based on a mixed-model analysis of variance, with fixed treatment and region effects and random block effects, as explained in Methods. Asterisks show results of a priori *t*-tests: treatment different from old growth, \**P* < 0.05; \*\**P* < 0.01.

Fish group	Old-growth	Buffered	Clear-cut	Treatment × region interaction <i>P</i>	Treatment effect <i>P</i>
<i>Summer</i>					
Coho salmon fry	65.9 (27.9–120.1)	167.6* (102.0–249.3)	164.0* (99.2–244.9)	0.07	0.04
Coho salmon parr	8.6 (4.3–14.6)	10.0 (5.2–16.2)	5.6 (2.3–10.6)	0.36	0.35
Dolly Varden parr	14.5 (2.0–38.4)	39.4 (15.2–75.1)	16.4 (2.8–41.4)	0.24	0.22
Trout parr	6.0 (1.1–14.8)	1.9 (0.0–7.7)	4.4 (0.5–12.3)	0.41	0.45
<i>Winter</i>					
Coho salmon fry	4.7 (1.5–9.7)	15.6* (9.1–23.8)	8.5 (4.0–14.9)	0.23	0.05
Coho salmon parr	3.8 (2.1–6.0)	4.9 (3.0–7.4)	0.2** (0.0–1.0)	0.08	0.005
Dolly Varden parr	13.4 (0.0–51.3)	17.2 (0.4–58.7)	9.0 (0.0–42.2)	0.90	0.82
Trout parr	10.4 (4.2–19.3)	3.0 (0.3–8.5)	1.8* (0.0–6.4)	0.20	0.07

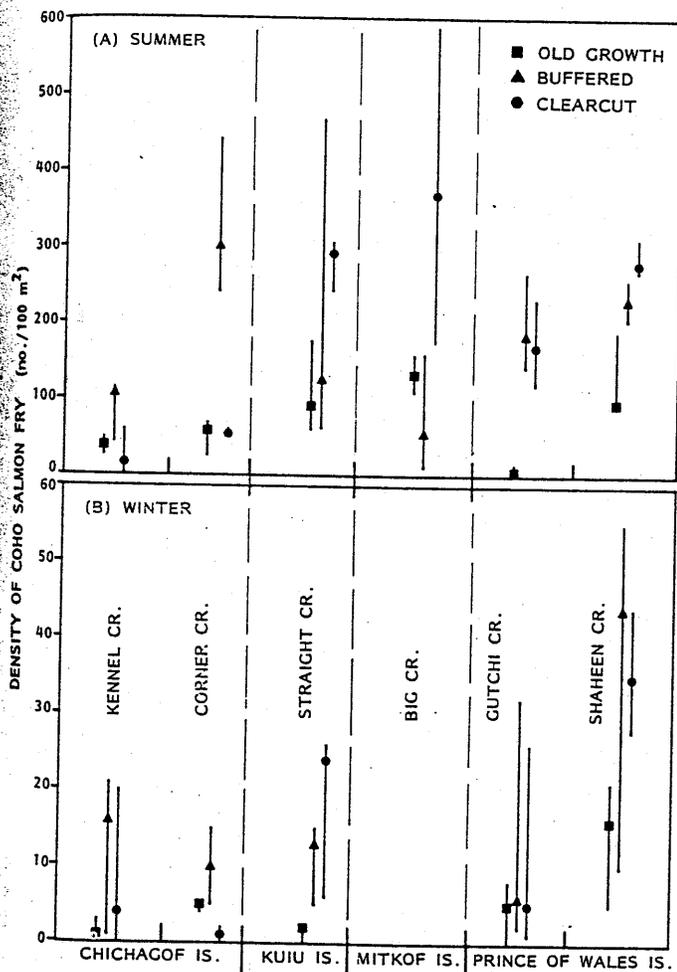


FIG. 5. Density of coho salmon fry in old-growth, buffered, and clear-cut reaches of the three streams in each of (A) six blocks in summer and (B) five blocks in winter. Points are medians; bars are ranges for the three reaches in each stream. Within a block, bars that do not overlap are significantly different (*P* = 0.05, median test). Names of the blocks refer to locations as in Fig. 1.

virtually no debris. All old-growth reaches and logged reaches in the northern blocks on Chichagof Island had sparse summer periphyton and a low winter density of fry (Fig. 6). Although some of these reaches contained a large volume of debris, the debris did not harbor many fry, presumably because fry densities were limited by low abundance of food in summer. The highest winter densities of fry were in certain buffered reaches, especially the Shaheen Creek reach with dense blowdown, where summer periphyton, benthos, and debris were all abundant.

#### Coho Salmon Parr

Coho salmon parr followed a different pattern of abundance from that of fry (Fig. 5 and 7). For example, in the southern and central blocks, where fry were more abundant in clear-cut than in old-growth reaches in summer, parr density in clear-cut reaches was similar to that in old-growth reaches in three blocks and less than that in old-growth reaches in one block. Thus, the greater abundance of fry in these clear-cut reaches was not associated with greater abundance of parr.

Unlike fry, parr were about equally abundant in old-growth, buffered, and clear-cut reaches in summer, but significantly less abundant in clear-cut than in old-growth reaches in winter (Table 4; Fig. 7). A mildly significant treatment × region interaction showed that logging effects in winter also tended to differ among the study locations. In the southern blocks, winter parr density in clear-cut reaches averaged only 3% of that in old growth; in the northern blocks, it averaged 76% of that in old growth, primarily because of the high density of parr in one clear-cut reach in the Corner Creek block. Without this reach, parr density in the northern block clear-cut reaches averaged only 6% of that in old growth. Buffered reaches, on the other hand, averaged 50% more parr than old-growth reaches in winter, but this difference was not significant (*P* > 0.35, *t*-test) because of variability in the buffered treatment. The high average parr density in buffered reaches was mainly due to the high density in a few reaches with dense blowdown in the Shaheen and Corner creek blocks.

Logging effects on density of coho salmon parr were related to effects on pools and debris. Summer density of parr was directly related to and best modeled by pool volume; winter density was directly related to pool volume, debris volume, and area of undercut banks and was best modeled by pool volume and debris volume (Table 5; Fig. 6). Cover in the form of debris and undercut banks was, thus, more important in winter than in summer, and reaches with the most pools, debris, and undercut banks harbored the most parr in winter.

Old-growth and buffered reaches usually had more pools and debris than clear-cut reaches; hence, most of the lowest winter parr densities were in clear-cut reaches where pool volume was low because debris had apparently been removed or washed from the reaches (Fig. 6 and 7). One of the highest winter densities, however, was in the clear-cut reach in the Corner Creek block where much natural debris remained and pool volume was high. The buffered reaches in the Shaheen and Corner creek blocks, with dense blowdown, harbored the highest and third-highest densities of parr in winter. Thus, treatment effects on winter parr density varied probably because of variable blowdown in buffer strips, as well as variable salvage and cleanup of debris from clear-cut reaches. Where debris was abundant, parr were abundant; where debris was removed, parr were scarce.

#### Dolly Varden Parr

Although average density of Dolly Varden parr was about two times greater in buffered than in old-growth and clear-cut reaches, treatment effects were not significant because they varied inconsistently among blocks (Table 4; Fig. 8). In winter, for example, buffered reaches had more parr than old-growth reaches in three blocks, but fewer parr in two blocks. Clear-cut reaches had more parr than old-growth reaches in one block, but fewer parr in another block. Treatment effects appeared to be masked by inherent differences in abundance of Dolly Varden among streams within blocks. For example, in the central blocks, Straight and Big creeks, Dolly Varden were absent from all the old-growth reaches yet were abundant in the buffered reaches. This difference existed in spite of these reaches having wide buffer strips and an appearance similar to old growth.

In both summer and winter, density of Dolly Varden parr was directly related to debris volume (Table 5) and was best modeled by a combination of debris volume and channel stability (Fig. 6): the more debris and the greater the stability, the higher the density of parr. In the buffered reaches with blowdown, high densities corresponded to large volumes of debris. The low densities of parr in most clear-cut reaches reflected low volumes of debris and low channel stability (Table 3). Thus, as with coho salmon parr, variable treatment effects on density of Dolly Varden parr were related to variable effects on habitat, especially debris.

#### Trout Parr

Density of trout parr did not differ significantly between old-growth and logged treatments in summer, but was significantly lower in clear-cut than in old-growth reaches in winter (Table 4). Although buffered reaches had only about one-third the trout density in old growth, this difference was not significant because of inconsistent differences among blocks (Fig. 9). In summer, for example, buffered reaches had fewer trout parr than in old growth in two blocks, but similar densities in four

TABLE 5. Product-moment correlations between fish density and habitat variables in summer and winter (\*significant at <5% level; significance level was set at  $\alpha/10$ , i.e. with significance level  $\alpha$  divided by the number of tests made for each fish variable). Reaches included are those with reliable population estimates, as described in Methods.

Habitat variable	Coho salmon		Dolly Varden parr	Trout parr
	Fry	Parr		
<i>Summer</i>				
Number of reaches	25	40	31	25
Stream width	0.32	0.00	-0.17	-0.65*
Channel gradient	-0.42	0.24	0.30	0.04
Fine sediment	-0.37	0.15	0.16	-0.18
Channel instability	0.40	0.17	-0.40	-0.32
Undercut banks	-0.02	0.15	0.13	0.19
Canopy density	0.00	0.20	0.12	0.02
Pool volume	-0.33	0.81*	0.20	-0.24
Instream debris	-0.03	0.38	0.46*	-0.24
Periphyton biomass	0.90*	-0.27	-0.41	0.00
Benthos density	0.67*	-0.55*	-0.43	-0.05
<i>Winter</i>				
Number of reaches	32	34	28	26
Stream width	0.54*	0.35	0.18	-0.07
Channel gradient	0.03	0.25	0.34	0.27
Fine sediment	-0.17	0.10	0.11	-0.44
Channel instability	0.38	0.16	-0.11	-0.24
Undercut banks	0.02	0.45*	-0.06	0.57*
Canopy density	-0.20	0.38	0.35	0.48*
Pool volume	0.18	0.79*	0.30	0.30
Instream debris	0.28	0.56*	0.77*	0.29
Periphyton biomass (summer)	0.63*	-0.29	-0.38	-0.16
Benthos density (summer)	0.55*	-0.36	-0.32	-0.23

blocks. Trout density also differed inconsistently between clear-cut and old-growth reaches in summer, but density was lower in clear-cut than in old-growth reaches in nearly every block in winter. Trout density in clear-cut reaches was 73% of that in old growth in summer, but only 17% of that in old growth in winter.

In summer, density of trout parr was significantly correlated with only one habitat variable — stream width (Table 5). Trout were less abundant in the larger streams (Fig. 6). The 12 old-growth and 8 clear-cut reaches in our subsample of reaches with reliable population estimates varied widely in both trout density and stream width, but the 5 buffered reaches had few trout, corresponding to their large stream widths. Thus, the low density of trout parr in buffered reaches (Table 4) may have been an artifact of the relatively large size of buffered streams in our sample.

Treatment effects on winter density of trout parr were related primarily to effects on undercut banks. In winter, density was no longer correlated with stream width, but was directly related to area of undercut banks (Table 5) and was best modeled by a combination of undercut banks and sediment: reaches with extensive undercut banks and little sediment had more trout parr in winter (Fig. 6). Old-growth reaches contained the highest winter densities of trout parr, which reflected their large areas of undercut banks and low amounts of fine sediment (Table 3). Buffered reaches varied widely in both trout density

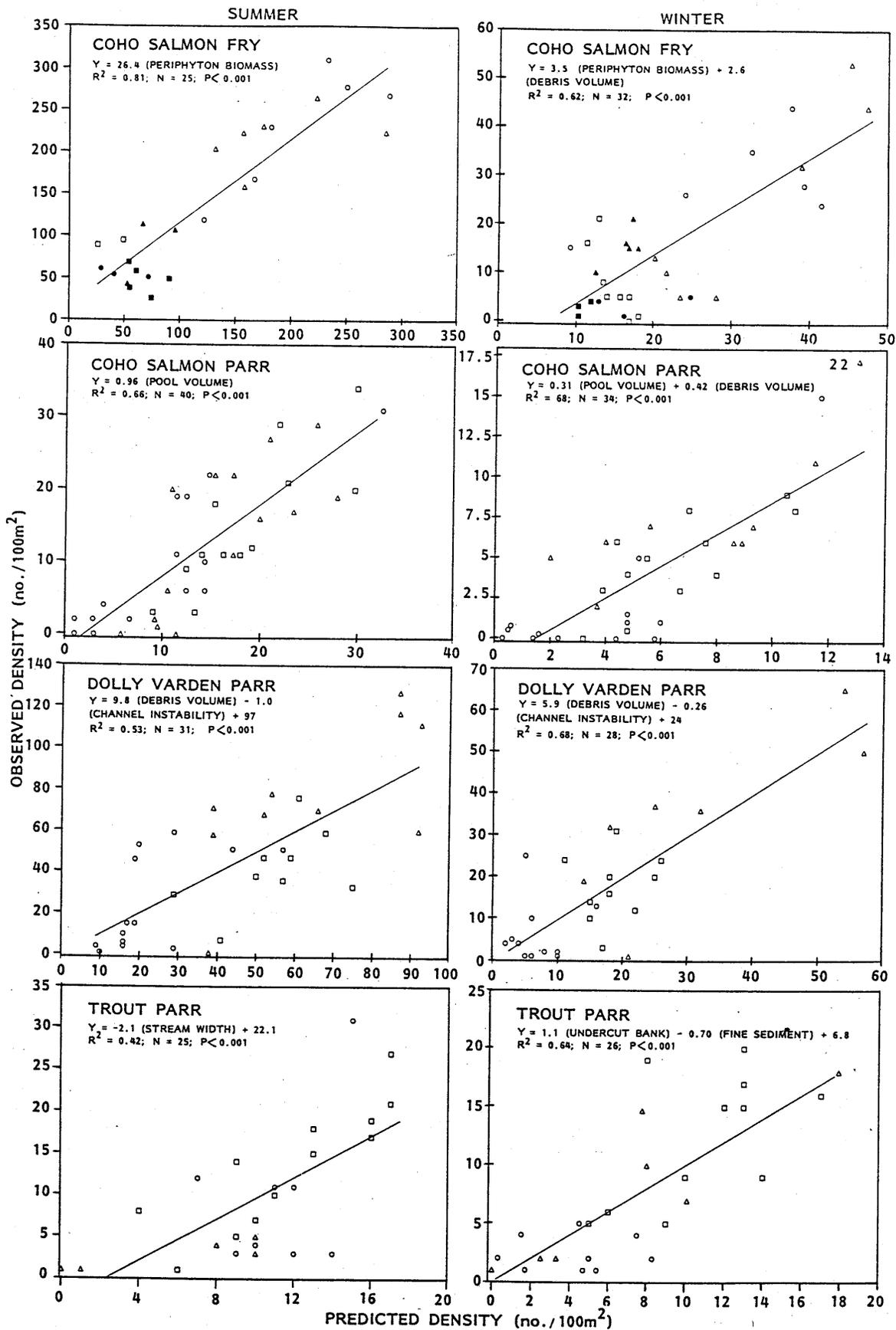


FIG. 6. Relationships between density of fishes in the old-growth (□), buffered (△), and clear-cut (○) reaches in summer and winter and that predicted by regression equations. Units of habitat variables are in Table 2. For coho salmon fry, solid symbols indicate reaches on Chicagof Island and open symbols indicate reaches on Kuiu and Prince of Wales islands.

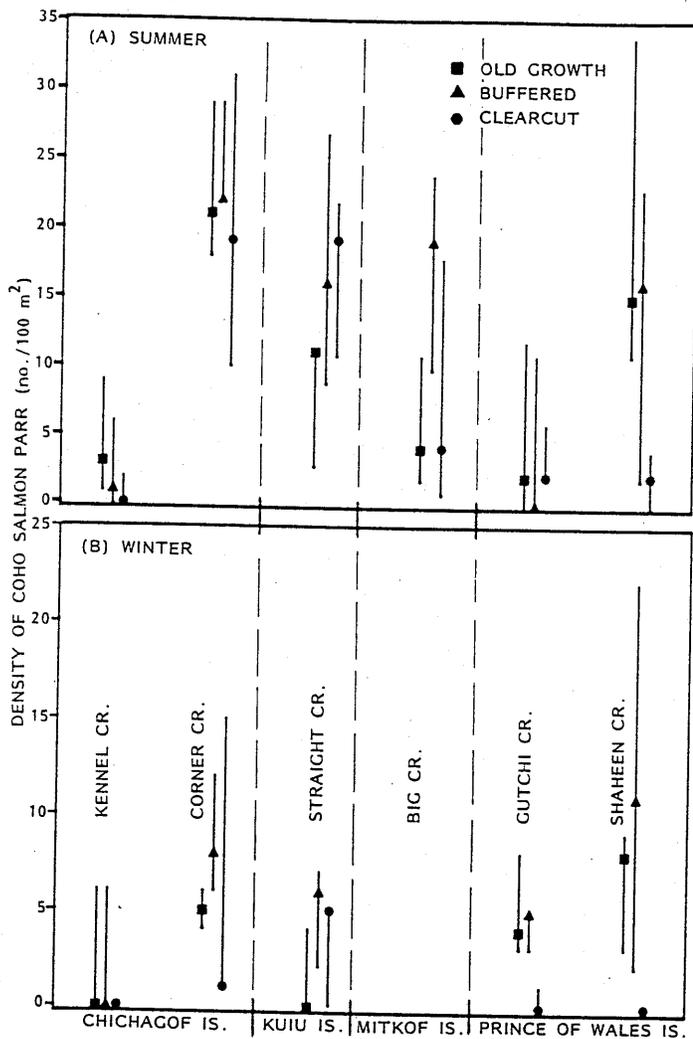


FIG. 7. Density of coho salmon parr in old-growth, buffered, and clear-cut reaches of the three streams in each of (A) six blocks in summer and (B) five blocks in winter. Points are medians; bars are ranges for the three reaches in each stream. Within a block, bars that do not overlap are significantly different ( $P = 0.05$ , median test). Names of the blocks refer to locations as in Fig. 1.

and undercut banks, whereas all clear-cut reaches had low trout density, which corresponded to their small areas of undercut banks.

## General Discussion

Effects of logging on juvenile salmonids can probably be best understood as a response to simultaneous, varied changes in both physical habitat and stream productivity, changes that affect different species and life stages of salmonids differently. In this study, amounts of periphyton, benthos, pools, debris, and undercut banks all differed between old-growth and logged reaches, but logging effects often varied depending on local conditions and logging practices. Effects of logging on salmonids were associated with these varied effects on habitat.

Logging often increases stream productivity for the first 10–15 yr because canopy removal increases the amount of light reaching the stream bed. In western Oregon and northern California, for example, logging increased aquatic primary production, benthos density, and fish density (Hansmann and

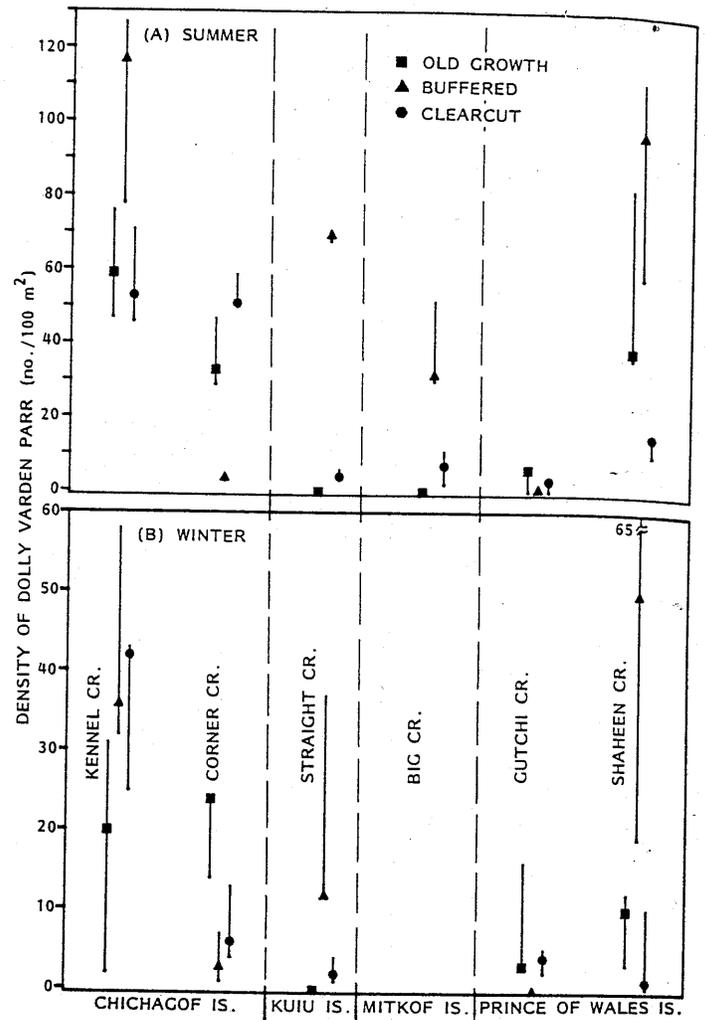


FIG. 8. Density of Dolly Varden parr in old-growth, buffered, and clear-cut reaches of the three streams in each of (A) six blocks in summer and (B) five blocks in winter. Points are medians; bars are ranges for the three reaches in each stream. Within a block, bars that do not overlap are significantly different ( $P = 0.05$ , median test). Names of the blocks refer to locations as in Fig. 1.

Phinney 1973; Lyford and Gregory 1975; Newbold et al. 1980; Murphy and Hall 1981; Hawkins et al. 1983). Similarly, shade of the old-growth forest canopy limited primary production in a stream in southeastern Alaska (Murphy 1984; Walter 1984). Low nutrients, however, can also limit primary production and preclude increased productivity after logging. Although logging increased the amount of light reaching Carnation Creek, primary and secondary production did not increase; production remained limited by low phosphorus (Shortreed and Stockner 1982; Culp and Davies 1983).

Changes in stream nutrients after logging vary. Nitrate concentration increased after clear-cutting in New Hampshire to more than 50 mg/L (Bormann et al. 1968) and in Oregon to 2 mg/L (Brown et al. 1973). After logging, nitrate concentration in Carnation Creek, British Columbia, increased to about 0.6 mg/L, but phosphate concentration remained extremely low at 0.003–0.004 mg/L (Scrivener 1982). In southeastern Alaska, clear-cutting and burning the watershed of a small stream on Chichagof Island altered neither nitrate nor phosphate, which averaged only 0.07 and 0.009 mg/L, respectively (Stednick et al. 1982).

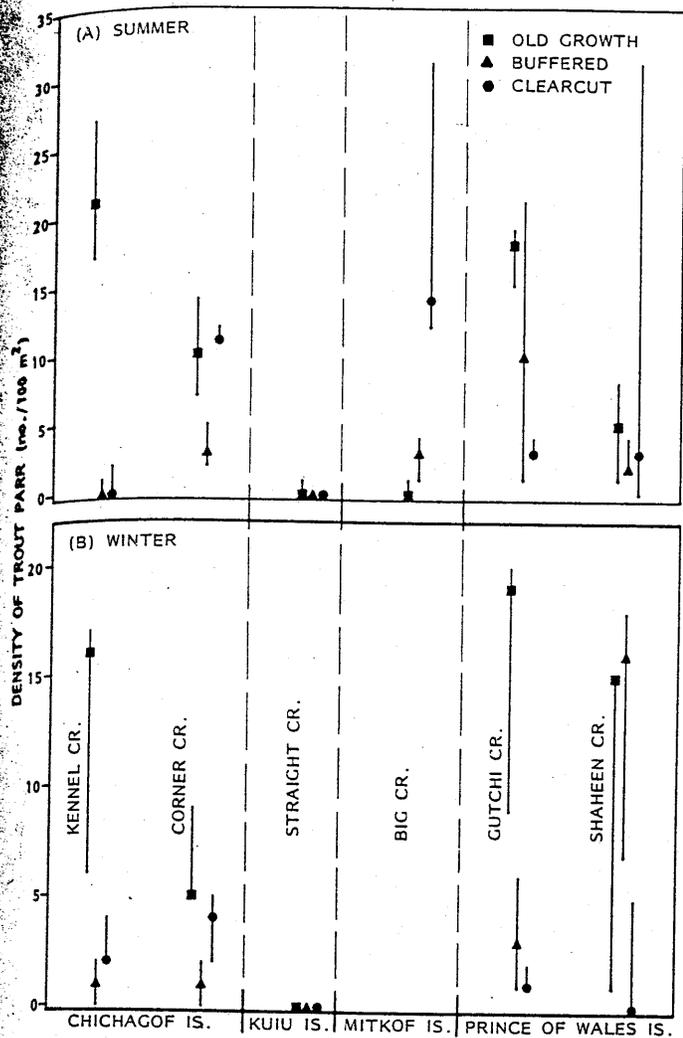


FIG. 9. Density of trout parr in old-growth, buffered, and clear-cut reaches of the three streams in each of (A) six blocks in summer and (B) five blocks in winter. Points are medians; bars are ranges for the three reaches in each stream. Within a block, bars that do not overlap are significantly different ( $P = 0.05$ , median test). Names of the blocks refer to locations as in Fig. 1.

Nutrient limitation may also explain why, in our study, logged reaches on Chichagof Island did not have more periphyton and benthos than reaches in nearby old-growth forest. Differences in response to canopy removal reflected the type of bedrock in the watersheds. The three blocks on Kuiu and Prince of Wales islands, with much more periphyton, benthos, and coho salmon fry in clear-cut than in old-growth reaches, had mostly sedimentary bedrock rich in limestone, whereas the two blocks on Chichagof Island, with little periphyton in logged reaches, had mostly igneous bedrock (Dutro and Payne 1954). Similarly, primary production was higher in clear-cut reaches of streams on Prince of Wales Island than in old-growth reaches of a stream on Etolin Island, southeastern Alaska (Walter 1984), both areas with limestone. However, primary production differed inconsistently between clear-cut and old-growth reaches on Chichagof Island (Weber 1981) in an area with mixed igneous and sedimentary rock.

Streams underlaid with limestone often have high concentrations of dissolved compounds, including phosphorus — a nutrient whose low concentration sometimes limits plant

growth — whereas streams in areas underlaid with igneous bedrock are poor in dissolved compounds (Golterman 1975). Thus, primary production may have been limited by light in watersheds with limestone and by nutrients in watersheds with igneous rock. Periphyton response to canopy removal, however, also followed a climatic gradient from greatest response in the southern and central streams to least response in the northern streams. Since we did not measure nutrients in the streams, we can only speculate on what caused the inconsistent effects of logging on periphyton biomass.

Differences in sampling time did not account for differences in periphyton between blocks. All streams within the three pairs of blocks — Straight and Big creeks, Gutchi and Corner creeks, and Shaheen and Kennel creeks — were sampled within 1 wk of each other, yet the clear-cut reaches within these pairs had very different amounts of periphyton (Fig. 3). Periphyton sampled at different times, therefore, differed less than periphyton sampled at different locations.

Summer density of coho salmon fry in many streams appears to be limited by low sunlight and availability of food (Chapman and Knudsen 1980; Hawkins et al. 1983; Bisson and Sedell 1984). Amounts of periphyton and benthos are only indirect measures of food availability for fish, yet the direct relationship between them and fry density in our study indicates that increased abundance of periphyton and benthos in some buffered and clear-cut reaches resulted in fry densities that were twice as high as in old-growth reaches. The high fry density in these logged reaches apparently resulted from a lower rate of emigration, as in experimental streams studied by Mason and Chapman (1965), because of reduced fry aggression and territory size (Dill et al. 1981).

Differences between treatments in fry density were probably not caused by differences in egg deposition by spawners. Treatment reaches within blocks were similar in distance from the stream mouth and were equally accessible to adult salmon. Furthermore, coho salmon fry may move long distances as they disperse from the spawning site (e.g. Crone and Bond 1976). Thus, recruitment of fry was potentially the same for all treatment reaches within the same block.

The benefit of increased productivity in clear-cut reaches could be nullified if fish die during winter because favorable habitat is lacking. For example, Mason (1976) increased the summer density of coho salmon fry in Sandy Creek, British Columbia, by feeding them, but the increase was nullified by mortality the next winter. In our study, the higher summer density of coho salmon fry in some buffered and clear-cut reaches, compared with old-growth reaches, was still apparent the next winter. In the clear-cut reaches from which debris was removed, however, fry density was reduced to less than that in comparable old-growth reaches. The winter of 1982, furthermore, was mild in southeastern Alaska. In more severe winters, mortality should be greater and debris more important.

Coho salmon in southeastern Alaska usually spend two winters in freshwater before going to sea (Crone and Bond 1976; Gray et al. 1981). If our data for the two age-classes, fry and parr, are viewed as a single cohort over 2 yr (i.e. assuming stable age structure), then the greater density of fry in the clear-cut reaches would be reversed during the fish's second winter in the stream. We did not, however, follow a year-class through both years and cannot be sure that a single cohort would follow this trend. Densities of coho salmon fry can vary greatly from year to year in a stream, but by the second summer, densities of parr may be consistently reduced to a narrow

range (Crone and Bond 1976). Thus, higher mortality or greater emigration probably caused the low winter density of coho salmon parr in most clear-cut reaches.

In clearcuts, this lower parr density could also be explained if fast-growing fry became smolts after only 1 yr. Average fry length did differ significantly among the old-growth, buffered, and clear-cut reaches in late winter (51, 54, and 56 mm, respectively; J. F. Thedinga, Auke Bay Laboratory, P.O. Box 210155, Auke Bay, AK 99821, unpubl. data). Thus, a tendency for fry to become smolts after only 1 yr could have contributed to the reduction in densities of older age-classes in the clear-cut reaches. The most likely explanation for lower parr densities in clear-cut reaches, however, is the reduction in preferred winter habitat. Most clear-cut reaches had few pools, scarce debris, and few parr, but some with good pool habitat and debris had many parr. Thus, loss of pools and debris, and not younger smolt age, probably accounts for the low winter density of parr in most clear-cut reaches.

Cover in the form of debris and undercut banks was more important for parr in winter than in summer, which probably explains why logging effects on parr density were significant in winter but not in summer. At summer temperatures, food abundance may override cover in determining abundance and distribution of parr within a stream (Wilzbach 1985). Studies on the impacts of logging on salmonids, therefore, may be misleading if data are taken only during summer.

Clear-cutting without buffer strips appears to reduce winter carrying capacity for salmonid parr by removing debris, collapsing undercut banks, and destabilizing or embedding channel substrate. This conclusion is supported by other studies. After logging, winter carrying capacity for coho salmon in Carnation Creek decreased as unstable debris washed downstream (Tschaplinski and Hartman 1983). Experimental removal of debris from a small stream in southeastern Alaska reduced Dolly Varden density by about 95% (Elliott 1986). Removal of undercut banks that provided cover for <2% of a stream in Montana reduced trout density by one third (Boussu 1954). Destabilization of a stream channel in western Washington by experimental removal of debris reduced winter trout density by one third (Lestelle and Cederholm 1984). Blowdown in buffer strips can uplift root masses and eliminate undercut banks, but in these cases, the added cover of debris may substitute for the lost cover of undercut banks (Heifetz et al. 1986).

Apparently, pools are lost from clear-cut reaches as natural debris is removed when logs are salvaged, logging slash is cleared from the stream channel, or destabilized debris washes downstream or floats onto the stream banks (Toews and Moore 1982; Bryant 1983; Bilby 1984). To prevent loss of pools and debris and to preserve channel stability, improved regulations are needed to prevent disturbance or removal of debris from salmon streams during logging. New guidelines being developed (U.S. Forest Service, 709 W. 9th St., Juneau, AK 99801, unpubl. data) should help prevent such disturbance and removal of debris.

Clear-cutting without buffer strips could maintain pools and debris in the short term if natural debris is protected, as it was in a few of the reaches in our study. In the long term, however, new debris is needed to replace the debris that decays or washes out of the stream during floods (Swanson and Lienkaemper 1978; Grette 1985). Even after 60 yr, debris from second-growth forest may not be adequate to maintain fish habitat, and debris volume and pool habitat decline (Grette 1985). To main-

tain production of salmonids after logging, debris must be maintained, and if properly managed, streamside areas can provide the needed debris.

The management practice of leaving streamside buffer strips appears advantageous. Buffer strips allow increased primary and secondary production, protect habitat, and provide a source for additional new debris after logging. Logging with buffer strips can, in the short term, increase recruitment of fry, yet sustain survival of fry and parr through winter. In the long term, buffer strips can provide new debris for the stream and thus maintain pools and debris through the next timber harvest.

Buffer strips, however, have not been widely used in southeastern Alaska because valuable timber is left in the woods, and buffer strips sometimes blow down. Blowdown provides valuable habitat for rearing salmonids, but too many trees in a stream can block fish passage or cover spawning areas. Severe blowdown can be avoided if buffer strips are thinned or designed to resist windthrow (Steinblums et al. 1984). Research is needed to determine the number and type of trees that should be left in buffer strips that would allow harvest of some of the most valuable trees, prevent excessive blowdown, and yet maximize benefits to fisheries.

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