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Alexander M. Milner
Mark W. Oswood Editors

Freshwaters of Alaska

Ecological Syntheses

Springer

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9. Alaska Timber Harvest and Fish Habitat

Michael L. Murphy and Alexander M. Milner

Fishing and timber harvest are major industries in Alaska. If not carefully planned and conducted, timber harvest and associated road construction may adversely affect anadromous fish habitat, which has sometimes brought these industries into conflict.

This chapter reviews forestry–fisheries interactions in Alaska, from the early research on the effects of timber harvest to the consensus and compromise of today. The review is organized around two main parts of salmon freshwater life history: spawning and rearing. Spawning is primarily affected by physical habitat variables; rearing is affected by both physical and trophic variables, requiring a broader understanding of the stream ecosystem.

Timber Resources in Alaska

Most of the Alaska timber harvest comes from coastal forests of western hemlock and Sitka spruce. Historically, the timber industry centered on the Tongass National Forest in southeast Alaska (Fig. 9.1); but harvest has recently increased on private lands in both southeast Alaska and coastal forests of southcentral Alaska, primarily Afognak Island and western Cook Inlet (ADCED, 1990). In 1991, the total Alaska timber harvest was 921 million board feet (MBF): 63% from private land, 35% from the Tongass National Forest, and 2% from other public lands (Warren, 1992).

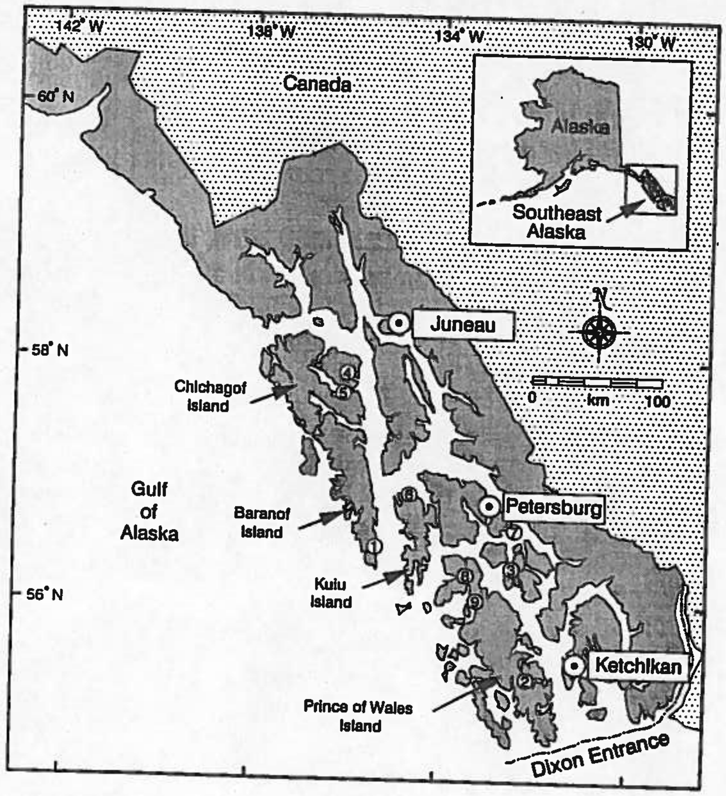
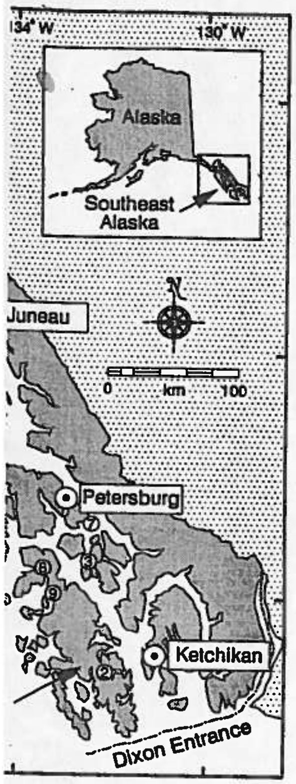


Figure 9.1. Map of southeast Alaska showing sites of research on timber harvest and fish habitat (1 = Sashin Creek; 2 = Hollis; 3 = Porcupine Creek; 4–9 = watersheds studied by Murphy et al. (1986): 4 = Kennel Creek; 5 = Corner Creek; 6 = Straight Creek, 7 = Big Creek; 8 = Gutchi Creek; 9 = Shaheen Creek). Most of southeast Alaska is in the Tongass National Forest.

In addition to its coastal forests, Alaska has extensive boreal forests in the interior, mostly on the intermontane plateau between the Alaska Range and the Brooks Range (Van Cleve et al., 1983). Boreal forests are dominated by white spruce, paper birch, poplars, and, on poorly drained soils, black spruce. These species are typically too small to be of commercial value, although the wood is good quality. The annual boreal timber harvest is small, about 13 MBF (Slaughter, 1990).

Timber management in coastal Alaska forests is based on even-aged silviculture on about a 100-year rotation (Harris and Farr, 1974). Trees are typically harvested by clear-cutting because this is economical and also favors regeneration of Sitka spruce. Logs are usually yarded to landings by high-lead systems and hauled by truck to facilities that transfer the logs to tidewater. Helicopter yarding is sometimes used where high-lead yarding is inappropriate and trees are of high value. Natural regeneration is usually



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relied on to restock cutover lands, which typically results in overly dense stands that benefit from thinning.

History of Forestry–Fisheries Research in Alaska

Forestry–fisheries research in Alaska has evolved through several phases (Gibbons et al., 1987). Before 1950, timber harvest was on a small scale and of negligible impact to fisheries. Since the 1950s, however, when timber harvest in southeast Alaska began to supply wood for the new pulp industry, effects of timber harvest on Alaska salmonid fisheries have become of increasing concern. From 1950 to the 1960s, research on effects of timber harvest focused on spawning habitat of pink and chum salmon, species that use freshwater streams solely for spawning. As timber harvest expanded from the 1960s through the 1970s, research shifted to the habitat requirements of species that spend several years in streams as juveniles before migrating to the sea (e.g., coho salmon and steelhead).

Since about 1980, forestry and fisheries groups have increased cooperation. The Alaska Working Group on Cooperative Forestry/Fisheries Research was formed in 1981. It consists of representatives of government resource agencies, the fishing and timber industries, and conservation groups, whose goal is to encourage studies to answer priority questions of streamside management (Simpson and Gibbons, 1984). Research and political compromise culminated in 1990 with the passage of the Tongass Timber Reform Act and revision of the Alaska Forest Resources and Practices Act, which prescribed new requirements for streamside buffer strips to protect salmonid habitat. Forestry–fisheries interactions now focus on implementing these new regulations and monitoring their effectiveness in protecting fisheries.

In the future, more commercial timber is likely to come from the coastal forests of southcentral Alaska and the interior boreal forests. Most research on the effects of timber harvest, however, has been conducted in southeast Alaska. Whether this research can be extrapolated to other regions of Alaska is questionable. Similar stream processes probably operate in these other regions, but forestry practices and the role of habitat in fish population dynamics could differ significantly. Consequently, further research is required to determine how timber harvest affects fish populations in the regions where harvest is expected to increase.

Effects of Timber Harvest on Spawning Habitat

Research on effects of timber harvest initially focused on spawning habitat. For successful spawning, adult salmon need access to gravel spawning beds with suitable permeability to water flow. Egg-to-fry survival is typically less than 25% in Alaska coastal streams, and increased mortality [illegible] caused by three factors: reduction in dissolved oxygen levels, freez[illegible] instability of spawning gravels (McNeil, 1964). Timber harvest can aff[illegible] spawning success by altering numerous habitat variables, including sediment, temperature, streamflow, and channel morphology and stability, and by interfering with adult migrations (Gibbons and Salo, 1973).

Sedimentation

Increased sediment from timber harvest can significantly impact fish habitat (Everest et al., 1987; Iwamoto et al., 1978). Sediment is usually classified into two categories: suspended sediment in the water column (typically clay and silt <0.1 mm diameter) and bedload sediment in the streambed (typically >1 mm) that can move during storms by rolling and bouncing along the stream bottom. Particles between about 0.1 and 1 mm may be suspended or bedload depending on streamflow. The sediments that are most important to the spawning environment are the fine sediments, usually defined as particles less than 0.88 mm diameter[1], that move into or out of the streambed depending on flow.

Fine sediment deposited in the redd can reduce egg-to-fry survival and fry quality by suffocating eggs and larvae, and by forming a physical barrier to emergence (Everest et al., 1987). Permeability of stream gravel decreases sharply as fine sediment increases from 5 to 20% of the substrate material (Fig. 9.2); egg to fry survival declines similarly (Fig. 9.3; Everest et al., 1987) because reduced permeability decreases the availability of oxygen and the flushing of metabolic wastes from incubating eggs and alevins. Coarser sediment can also reduce spawning success by capping gravels and restricting the emergence of alevins. Egg-to-fry survival of coho salmon in Sashin Creek, Baranof Island (Fig. 9.1), was reduced by sediment <1.7 mm diameter (Crone and Bond, 1976). Mortality associated with low dissolved oxygen ($<4\,mg\,L^{-1}$) in three Prince of Wales Island streams near Hollis (Fig. 9.1) ranged from 60 to 90% of deposited eggs (McNeil, 1964).

Logging roads are typically the greatest sediment source associated with timber harvest in Alaska. Sediment delivery to streams in two Chichagof Island watersheds during road construction was about $100\,m^3\,km^{-1}yr^{-1}$ of road compared to only $0.2\,m^3 km^{-1}\,yr^{-1}$ from lightly used roads after construction (Swanston et al., 1990). Monitoring, however, indicated that best management practices (BMPs, regulations controlling the manner of harvest and road construction) limited sediment inputs from road construction to levels within the natural range; suspended sediment reached $277\,mg\,L^{-1}$ at

[1] The 0.88 mm diameter size corresponded to a particular sieve size used in the research that demonstrated detrimental effects on egg-to-fry survival from particles passing through that sieve.

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high streamflow but was generally lower (Paustian, 1987). In comparison, suspended sediments reached 320 $mg L^{-1}$ in a Chichagof Island old-growth forest (Campbell and Sidle, 1985).

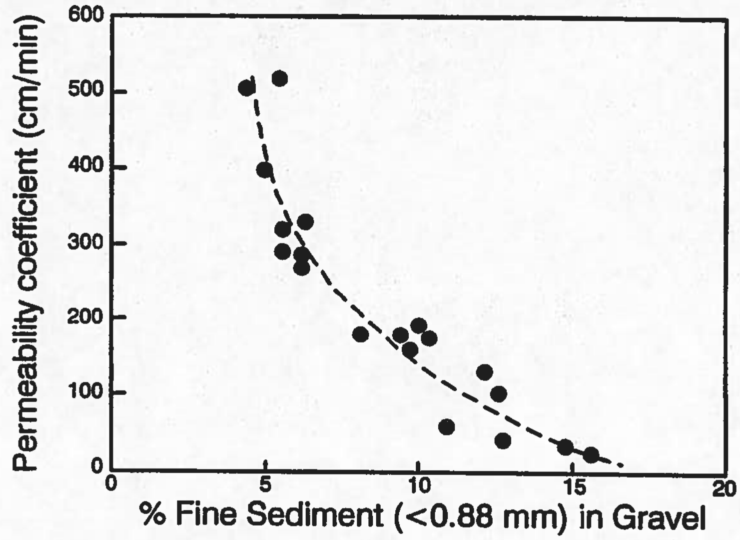

Figure 9.2. Relationship between gravel permeability and percentage of sediment less than 0.88 mm (after McNeil, 1964).

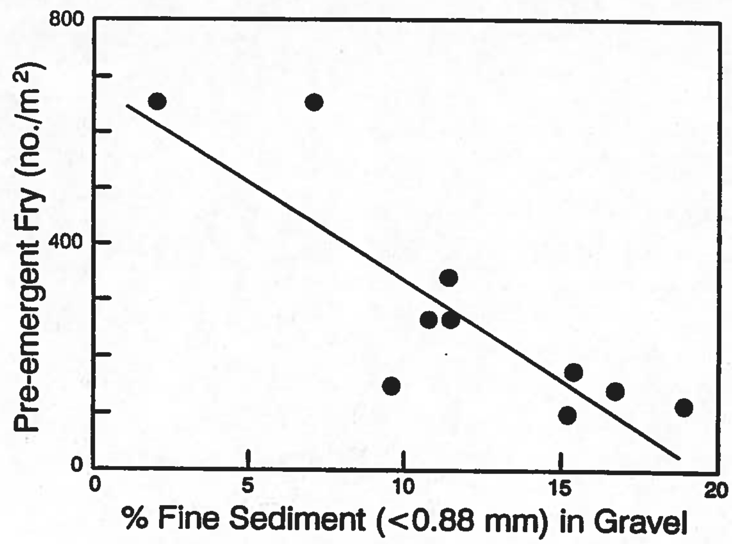

Figure 9.3. Relationship between pink salmon egg-to-fry survival and percentage of fine sediment. Correlation $r = 0.86$ (after Koski, 1972).

Figure 9.4. Log hauling on a gravel road during a dry spell on Kuiu Island, southeast Alaska (photo T.R. Merrell, Jr. 1982).

Regular road use can cause chronic sediment input to streams. Because of weak rock material, the gravel road surface in many areas of southeast Alaska breaks down with repeated heavy wheel loads of hauling trucks (Fig. 9.4), particularly under wet conditions, resulting in a continual source of fine sediment to streams (Powell, 1989). Sediment produced by log hauling is estimated at $50 m^3 km^{-1} yr^{-1}$ of road (Swanston et al., 1990). Lack of knowledge about the process of sediment delivery from roads to streams, however, makes the effects of road sediment on fish spawning success difficult to predict.

Road failure is a concomitant risk of road construction in mountainous terrain (Furniss et al., 1991). Severe gullying and landslides may result if roads intercept and concentrate runoff and discharge it into nondrainage areas. Stream crossings (i.e., culverts and bridges) pose the greatest risk to fish habitat of any road feature. When culverts are plugged by debris or overtopped by high streamflow, stream channels may realign and sedimentation may be severe. The risk of failure of a crossing structure depends on its size compared to flood events, and culverts should be sized to accommodate at least a 50-year flood (Furniss et al., 1991). Whatever the design life, any crossing structure is virtually certain to fail if it is not maintained or removed after the road is abandoned.

Compared to roads, tree felling and yarding away from streambanks usually produce negligible sediment due to several factors that limit surface

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erosion (Everest et al., 1987). In southeast Alaska, coarse-textured soils with thick organic surface layers, high soil permeability and infiltration, and rapid revegetation of disturbed soils tend to limit sediment production from tree felling and yarding.

Felling and yarding along streambanks, however, can produce sedimentation by mobilizing sediment stored in the stream channel and flood plain. Disturbing the stream channel during felling and yarding, introducing logging slash, and salvaging merchantable logs from the flood plain can cause significant scour and deposition (Fig. 9.5). Landslides also can increase because of tree removal (Schwan et al., 1985) because increased snow accumulation in clear-cuts increases downslope weight (Hartsog, 1990). Frequency of landslides in the Maybeso Creek watershed, Prince of Wales Island, increased 4.5-fold after timber harvest (Bishop and Stevens, 1964), and the increased risk of landsliding appears to be long term. Heavy rainfall in October 1993 triggered numerous landslides in second-growth areas of Prince of Wales Island at a frequency more than four times that in old-growth areas (Landwehr, 1994).

The effects of timber harvest on sedimentation are difficult to assess because of natural variation in sediment dynamics. Paustian (1987) highlighted the difficulty of detecting changes in suspended sediment after timber harvest because of extreme natural variation due to seasonal changes in discharge and storm events. Redd digging by salmon also re-

Figure 9.5. Destabilization and erosion of a stream channel after clear-cut logging (photo T.R. Merrell, Jr., 1982).

moves fine sediment from the streambed, so that sediment content in redds after digging is temporarily less than in the surrounding area (McNeil and Ahnell, 1964). Mean percentage of fine sediment in spawning gravels ranges from about 6 to 14% in undisturbed watersheds in southeast Alaska (Edgington, 1984; Kingsbury, 1973). Sheridan et al. (1984) found no significant difference in mean percentage of fine sediment in spawning riffles between six streams in logged areas (5 to 15% fines) and six in undisturbed areas (5 to 12% fines). Nevertheless, a 10% increase in fine sediments in spawning gravels may be undetectable because of natural variability, but could still reduce egg to fry survival (Edgington, 1984).

Early studies near Hollis found conflicting evidence concerning the effects of timber harvest on spawning gravel. The first studies indicated that sediment production was not significantly greater in logged watersheds (Alaska Forest Research Center, 1957, 1960). Later, however, Bishop and Stevens (1964) found that sedimentation rate was four times the natural rate. McNeil and Ahnell (1964) also reported two to four times more fine sediment in the Harris River during timber harvest, but could not conclusively identify timber harvest as the sediment source because of high variability. Sediment returned to normal 5 years after logging ceased (Sheridan and McNeil, 1968). In 108 Creek, fine sediment in spawning gravel increased 6 to 8% during timber harvest and remained elevated for 3 years (Kingsbury, 1973). Pella and Myren (1974) questioned the validity of the early Hollis studies because streambed sediment and egg-to-fry survival were not monitored long enough to evaluate long-term effects.

Although the effects of sediment from timber harvest are not well established for southeast Alaska, adverse effects have been documented by long-term studies in British Columbia (Holtby and Scrivener, 1989) and Washington (Cederholm et al., 1981). In Carnation Creek, British Columbia, for example, increased fine sediment in spawning gravels after timber harvest contributed to a 25% reduction in chum salmon escapement (Holtby and Scrivener, 1989). The Southeast Alaska Multiresource Model, developed by the U.S. Forest Service and based principally on Alaska research, indicated for a model 1,600-ha watershed that typical timber harvest and roading could increase fine sediment in spawning gravels by 160% and decrease pink salmon returns by 35% (from 275,000 to 180,000), with recovery taking 12 years (Garrett et al., 1990).

New road construction for timber harvest in Alaska could significantly impact spawning habitat. Under current projections, roads in the Tongass National Forest (now totaling 4800 km) would increase to over 14,000 km in 50 years (U.S. Forest Service, 1991). Impacts of sedimentation from these and other private logging roads are difficult to predict. Risks of impacts—from road failures, washout of culverts and bridges, and failure of culverts to pass fish—increase with the kilometers of roads constructed.

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Temperature

Water temperature affects development and survival of salmonids at all life stages. Temperature regulates the development rate of eggs and larvae, and each life stage has an optimal temperature range with upper and lower lethal limits (Weber-Scannell, 1991). Removing the forest canopy by timber harvest along streams, especially where no buffer strips are present, can increase average stream temperature and its daily fluctuation. Stream size, gradient, orientation, and stream length open to sunlight determine the magnitude of temperature increases (U.S. Forest Service, 1986).

Research on effects of timber harvest on stream temperature in southeast Alaska began in 1949 near Hollis with intensive studies on four drainages: two to be harvested (Harris River and Maybeso Creek), and two unharvested controls (Indian Creek and Old Tom Creek). The first studies (Harris, 1960; James, 1956) reported no change in temperature after timber harvest. Further studies, however, showed that timber harvest increased the maximum summer temperature as much as 5°C, and the average increase in monthly maximum temperature was 2.2°C (Meehan et al., 1969).

Later, extensive studies found that temperature in small southeast Alaska streams in clear-cuts reached 23°C (Tyler and Gibbons, 1973), approaching the lethal levels for salmon of about 25 to 30°C (Bjornn and Reiser, 1991). The rate of warming per 100-m length of stream was 0.92°C in one clear-cut compared to 0.07°C in old-growth forest (Tyler and Gibbons, 1973). In a study of 13 southeast Alaska streams (Meehan, 1970), the largest increase in a clear-cut was 2.3°C in a 183-m reach (equal to 1.25°C $100\,m^{-1}$), but temperature did not approach lethal levels. The increase in stream temperature after timber harvest is directly proportional to the area of stream exposed to solar radiation and inversely proportional to streamflow (Beschta et al., 1987).

Effects of increased stream temperature in summer are a lesser problem in most southeast Alaska streams than in more southerly states and other Alaska areas because of southeast Alaska's cooler and cloudier weather (Gibbons et al., 1987). Some southeast Alaska streams, however, are "temperature sensitive" because of their specific characteristics, and temperature can rise to undesirable levels if shade canopy is removed (Gibbons et al., 1987). Streams most likely to be temperature sensitive are relatively wide, shallow, low-gradient streams with lake or muskeg sources (U.S. Forest Service, 1986).

Temperature is particularly important for regulating the rate of egg development, and increased temperature during the incubation period can cause fry to emerge early. Thedinga et al. (1989) estimated that because of increased temperature, primarily in spring, coho salmon fry in two southeast Alaska watersheds could emerge 37 days earlier in clear-cut reaches

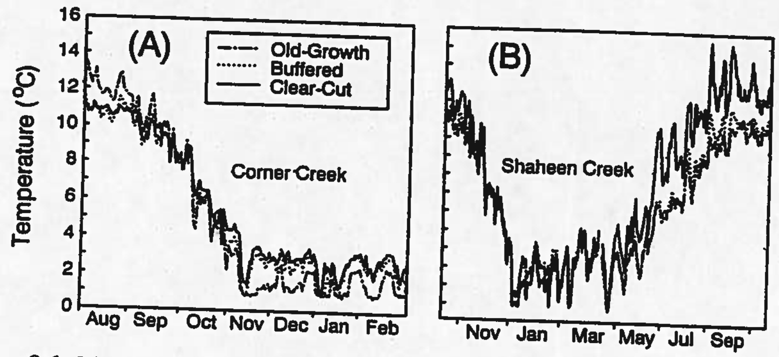


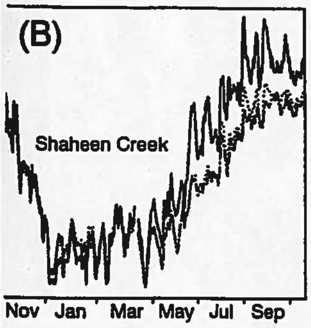
Figure 9.6. Mean daily water temperature in old-growth, buffered, and clear-cut reaches of streams in 1982–1983 in two watersheds: (**A**) Corner Creek, Chichagof Island, and (**B**) Shaheen Creek, Prince of Wales Island (after Thedinga et al., 1989).

and 22 days earlier in reaches with buffer strips than in old-growth reaches (Fig. 9.6). During the incubation period (November to May), clear-cut and buffered reaches accumulated 21 and 12%, respectively, more temperature units (degree-days) than old-growth reaches. Early emergence can be harmful because it exposes fry to floods in early spring (Hartman et al., 1984).

Timber harvest is also thought to decrease stream temperature in winter because insulating canopy is removed, but research results are equivocal. Meehan et al. (1969) reported little or no difference between winter temperature of southeast Alaska streams in logged and in forested areas. Thedinga et al. (1989) found higher winter temperature in an old-growth reach than in a clear-cut reach in one watershed, but the opposite in a second watershed (Fig. 9.6). Timber harvest may actually increase winter temperature by increasing soil insolation, as demonstrated for the Carnation Creek watershed in British Columbia (Hartman et al., 1984). Although the overall effects of timber harvest on winter temperature have not been clearly demonstrated, concern is warranted. Winter stream temperature is usually near 0°C and typically varies within a small range (Lamke et al., 1991). Small temperature shifts in winter can thus significantly influence incubating eggs and overwintering juveniles.

Streamflow

Timber harvest effects on streamflow can influence spawning success by altering the hydrologic regime. This regime responds to changed distribution of water and snow on the ground, rate of snowmelt, precipitation intercepted by and evaporated on foliage, amount of water transpired from soil by vegetation, and physical structure of the soil governing rate of water movement to stream channels (Chamberlin et al., 1991). The effects on streamflow that most concern fisheries managers are changes in base and peak flows.



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Base flow usually increases during the first 10 to 20 years after timber harvest because removing trees decreases interception of precipitation and evapotranspiration (Chamberlin et al., 1991). Increases in base flow are greatest during the summer growing season. Later, in the rainy season (fall to winter), the soil is saturated and runoff is similar in both clear-cut and forested areas. After 10 to 20 years, base flows may actually decrease below preharvest levels because of greater evapotranspiration in rapidly growing second-growth forest (Harr, 1983; Hicks et al., 1991; Myren and Ellis, 1984). In southeast Alaska, base flow in Staney Creek (drainage area, 134 km²), Prince of Wales Island, increased significantly after about 20% of the watershed had been harvested (Bartos, 1989).

Peak flow may also increase after timber harvest. Activities that disturb and compact the soil, such as road construction and yarding, reduce soil permeability causing more surface runoff and high peak flows. Ditches along roads collect surface runoff and intercept subsurface flow, also contributing to higher peak flows. More accumulated snow and faster melting rate in clear-cut areas causes higher peak flows during rain-on-snow events and spring snowmelt (Golding, 1987; Chamberlin et al., 1991). Higher peak flows are considered detrimental to fish because bed load overturn, which occurs during high flows, can kill many incubating eggs (McNeil, 1964; Murphy et al., 1990). Watershed geology may modify the effects of increased peak flow. Based on five gaged southeast Alaska watersheds, Bartos (1993) concluded that peak flows increased after timber harvest in three watersheds with metamorphic geology, but decreased in two watersheds with abundant limestone. The role of geology in determining effects of timber harvest on peak flows was unexplained.

Channel Morphology and Stability

Channel morphology in small streams is formed primarily by large woody debris (LWD), usually defined as tree boles, branches, and roots greater than 10 cm diameter and 1 m long (Bisson et al., 1987; Sullivan et al., 1987). Large woody debris plays an important role in creating spawning habitat in small streams. By forming pools, LWD increases the frequency of pool–riffle transition areas, where many salmonids prefer to spawn (Bjornn and Reiser, 1991). In gravel-poor streams, gravel deposits upstream from LWD can provide suitable spawning substrate (Everest and Meehan, 1981). In sediment-rich streams, the scouring caused by flow obstructions like LWD benefits spawning fish by sweeping fines out of spawning beds (Sedell and Swanson, 1984).

Timber harvest can affect spawning habitat significantly by altering LWD. Accumulations of LWD in Maybeso Creek decreased in size and number for 30 years after timber harvest (Bryant, 1980), and similar changes occurred in the Harris River (Bryant, 1985). Logging slash is less stable and less effective in forming fish habitat than LWD from natural sources; and when slash moves, it can destabilize natural LWD accumulations downstream (Bryant, 1980).

Channel stability is also important in determining egg-to-fry survival. Shifting of gravel and unstable LWD during floods is an important mortality factor in coastal streams (McNeil, 1964). Bedload overturn is a function of high water velocity during peak streamflows, and increased peak flows after timber harvest increase the risk of bedload overturn (Swanston et al., 1990).

Adult Migration

Timber harvest can interfere with adult migration by blocking migrations at stream crossings of logging roads, by causing logjams that block migration, by decreasing cover from predators, by decreasing the frequency of large pools used for resting, and by adversely affecting temperature and amount of dissolved oxygen.

Culverts, especially those installed above the grade of a stream, can be a barrier to upstream fish migration (Furniss et al., 1991). Culvert conditions that block fish passage include too fast water velocity, too shallow water depth, no resting pool below culvert, and too high a jump to the culvert. A single poorly installed culvert can eliminate the fish population of an entire stream system.

Before regulations were adopted to limit logging slash entering streams, accumulated slash from timber harvest could block upstream migrations of adult salmon (Fig. 9.7), and much effort was spent on removing these logjams (Bisson et al., 1987; Hall and Baker, 1982). The severity of these blockages has been reduced by the mandated removal of logging slash from streams after timber harvest, and today streamside buffer strips restrict logging slash from entering streams. Further, natural logjams that appear to be blockages often allow fish to pass at high flows during migration (Bryant, 1983).

Decreases in large pools and cover can also affect spawning migrations. Adult salmon often hold for several weeks in large pools when ascending a stream to spawn (Burger et al., 1985; Thedinga et al., 1993). The number of suitable large pools for adult holding can be limited along a stream. Timber harvest can decrease the number of large pools by removing, reducing, or destabilizing the large "key" pieces of LWD that create these pools (Sedell and Everest, 1990).

Prespawn die-offs of adult pink and chum salmon are not uncommon in southeast Alaska, particularly in drier summers (Murphy, 1985); and timber harvest has been implicated by increasing stream temperature. In 1989, for example, die-offs ranging from hundreds to 54,000 were documented in 19 streams (ADEC, 1990).

From the available record, prespawn die-offs occur in both logged and ıbilize natural LWD accumula-

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the grade of a stream, can be a
et al., 1991). Culvert conditions
ter velocity, too shallow water
o high a jump to the culvert. A
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logging slash entering streams,
d block upstream migrations of
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r, 1982). The severity of these
d removal of logging slash from
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, natural logjams that appear to
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ıga et al., 1993). The number of
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ı salmon are not uncommon in
ers (Murphy, 1985); and timber
ream temperature. In 1989, for
54,000 were documented in 19

-offs occur in both logged and

forested stream reaches. Most streams that have summer drought-related die-offs have several characteristics in common:

1. small drainage area (<50 km^2);
2. headwater elevation from 300 to 450 m (hence, little snow pack);
3. absence of lakes, ponds, and beaver dams that would help to maintain streamflow during drought;
4. extensive low-elevation, shallow muskeg-pond tributaries that contribute to high water temperature during sunny periods; and
5. confined intertidal systems that restrict tidal exchange (Brown, 1989).

Die-offs can be triggered when returning adults follow the flood tide into a stream, and then are stranded in pools as the tide ebbs (Murphy, 1985).

Because of the public controversy about the role of timber harvest in prespawn die-offs, the Alaska Working Group on Cooperative Forestry/

Figure 9.7. Logging slash completely filling a stream channel (photo M.W. Oswood).

Fisheries Research initiated research to determine the cause of these summer die-offs. Murphy (1985) concluded that a die-off of pink and chum salmon in Porcupine Creek (an old-growth forest stream) was not directly due to high temperature (which did not exceed 19°C), but to suffocation from low dissolved oxygen ($<2\,mg\,L^{-1}$), a result of stranding and crowding in shallow water. After examining the concentration of dissolved oxygen in pools of seven streams in southeast Alaska in August 1990, Martin et al. (1991) also concluded that the most likely cause was oxygen depletion from fish respiration during low streamflow.

Effects of timber harvest on prespawn die-offs are still uncertain. High stream temperature from canopy removal may contribute to mortality by lowering the saturation concentration of oxygen in water and increasing fish respiration. Timber harvest also reduces evapotranspiration, increasing the summer base streamflow, that could make die-offs less severe (Murphy, 1985). However, a possible decrease in base streamflow 10 to 20 years after timber harvest could reverse this trend (Myren and Ellis, 1984; Hicks, Hall, et al., 1991).

Effects of Timber Harvest on Rearing Habitat

Research on spawning habitat addresses only one aspect of salmonid habitat requirements and does not examine the influence of timber harvest on species limited by the quality and quantity of rearing habitat: juvenile coho salmon, steelhead, cutthroat trout, and Dolly Varden. If spawning escapement is adequate, sufficient fry are usually produced to exceed the carrying capacity of available rearing habitat (e.g., Crone and Bond, 1976). Reduced spawning success in rearing-limited populations would not necessarily reduce smolt yield because of a compensatory density-dependent response at later stages (Bjornn and Reiser, 1991; Everest et al., 1987) as long as effects are not too severe and sufficient fry continue to be produced to fully seed available habitat.

Smolt yield is considered the key variable in assessing effects of timber harvest on rearing-limited species (Koski et al., 1985). The number of returning adults may be the ultimate measure of timber harvest effects, but it is confounded by widely varying marine survival factors (Pella and Myren, 1974). Timber harvest can still affect marine survival of smolts, however, particularly by altering a stream's trophic status and temperature regime. Increased temperature, for example, can cause smolts to migrate to sea early, as observed in a Carnation Creek study by Holtby and Scrivener (1989). They speculated that earlier smolt migration after timber harvest caused a net decrease in adult returns, even though it caused an increase in smolt yield. Earlier smolt migration is thought to reduce ocean survival because smolts enter saltwater before plankton food sources have bloomed, slowing their growth and increasing predation.

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Effects of timber harvest on rearing habitat are more complicated to assess than effects on spawning habitat. Successful rearing depends on both physical and trophic factors and their interaction. As predators, salmonids are influenced by all trophic levels in the stream ecosystem, from primary production to decomposition, as well as by physical conditions of the habitat (Murphy and Meehan, 1991).

The predominant habitat features of streams in old-growth forest are an abundance of LWD, a mix of deciduous and coniferous leaf litter and woody debris, and canopy gaps that allow algal growth on the stream bottom (Sedell and Swanson, 1984; Fig. 9.8). Clear-cutting without buffer strips can reduce LWD by removing debris from stream channels after yarding, destabilizing LWD accumulations leading to their downstream export, salvaging downed logs from the flood plain, and reducing the supply of potential new LWD. Clear-cutting can severely reduce the diversity of stream habitats, with scant LWD in the stream channel and a long-term shortage of new supply (Fig. 9.9). Buffer strips (Fig. 9.10) were rare in southeast Alaska before the late 1980s because of the monetary value of streamside trees and the tendency of buffer strips to be blown down (Fig. 9.11). Concern about effects of timber harvest on rearing habitat prompted research to determine the effects of clear-cutting and the effectiveness of buffer strips in protecting stream habitat.

Figure 9.8. Typical section of a valley-bottom stream in old-growth forest in southeast Alaska (photo T.R. Merrell, Jr., 1982).

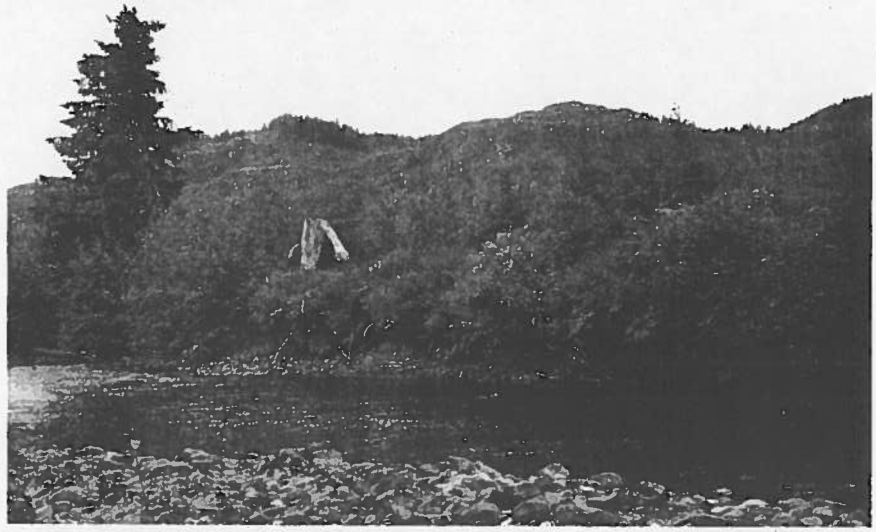

Figure 9.9. Stream flowing through a clear-cut area without a streamside buffer strip before the Tongass Timber Reform Act of 1990 (photo T.R. Merrell, Jr., 1982).

Figure 9.10. A streamside buffer strip used to protect fish habitat along a southeast Alaska stream before the Tongass Timber Reform Act of 1990 (photo T.R. Merrell, Jr., 1982).

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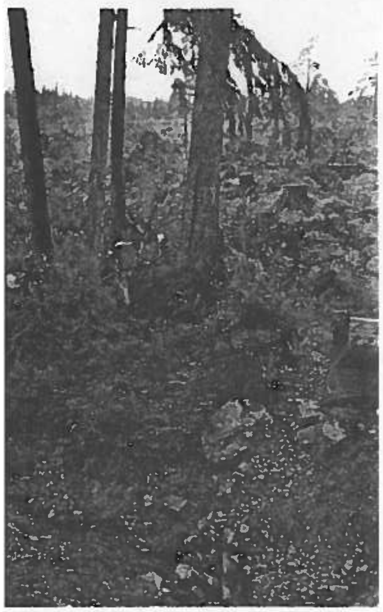

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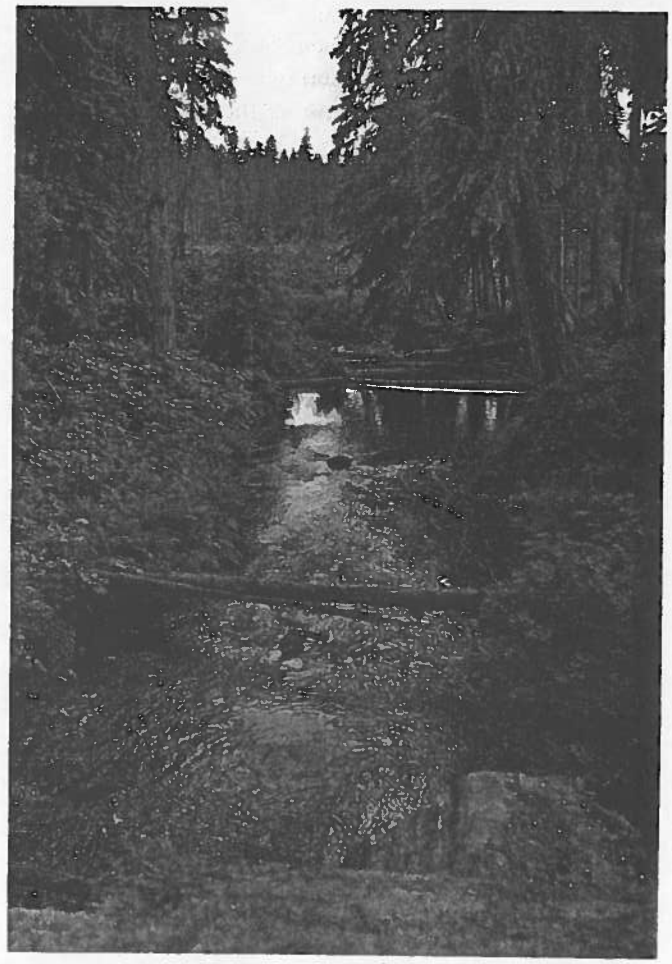

Figure 9.11. Wind-thrown trees in a streamside buffer strip (photo T.R. Merrell, Jr., 1982).

To assess overall effects of timber harvest on rearing habitat of juvenile salmonids, one has to consider specific limiting factors ("bottlenecks") over the entire juvenile period. For the analysis of limiting factors, the rearing period is typically divided into summer and winter periods dominated by different habitat components (Reeves et al., 1989).

Summer Rearing

In summer, effects of timber harvest on juvenile salmon appear to be more related to food supply than to physical factors. Stream ecosystems have two energy sources: in-stream primary production (autochthonous sources) and out-of-stream sources of organic matter (allochthonous input) (Murphy and Meehan, 1991). Timber harvest can affect both these sources by altering riparian vegetation and other physical conditions in the stream, such as temperature, nutrients, stream morphology, and sediment. Effects vary from reach to reach, and through time as the riparian plant community passes through stages of recovery.

Removing the forest canopy increases insolation of the streambed, which can increase aquatic primary production (Gregory et al., 1987; Murphy and Meehan, 1991). Where light is limiting, the predominant energy source for the stream ecosystem shifts from allochthonous to autochthonous production for the first 10 to 20 years after timber harvest. For example, primary production was significantly higher in clear-cut reaches of tributaries of Staney Creek, Prince of Wales Island, than in old-growth Porcupine Creek, and was negatively correlated with percent canopy cover in Porcupine Creek (Walter, 1984). In three small streams on Prince of Wales Island, periphyton production and community respiration were higher in a recently clear-cut stream than in old-growth and second-growth streams (Duncan and Brusven, 1985a), and experimental removal of second-growth riparian alder increased primary production (Bjornn et al., 1992).

Although most Alaska studies have shown increased primary production after canopy removal, indicating light limitation, some streams show no response to increased light, probably because of nutrient limitations. Nitrate and phosphate levels in a Chichagof Island stream were only 0.07 and 0.009 mg L^{-1}, respectively, levels not increased by clear-cutting and burning (Stednick et al., 1982). Rapid revegetation also helps to limit nutrient losses from the soil after timber harvest, and any increases in nutrient input to streams are usually small (Brown, 1972). In southeast Alaska watersheds underlain by sedimentary rocks such as limestone, streams are likely to be light limited; but where the parent material is igneous, streams may be nutrient limited (Murphy et al., 1986; Fig. 9.12).

The increased algal production after clear-cutting results in more abundant benthic invertebrates (Duncan and Brusven, 1985b). The density of invertebrates in old-growth, buffered, and clear-cut streams was directly related to biomass of algae (Fig. 9.13; Murphy et al., 1986). Removal of second-growth riparian alder increased both algal production and abundance of benthic invertebrates (Bjornn et al., 1992).

Although the predominant energy source changes after timber harvest, the dominant macroinvertebrates and functional feeding groups may remain unchanged (Duncan and Brusven, 1985b; Hawkins et al., 1982). Collector–gatherers dominate in both shaded and open stream reaches because much algal production is used as organic detritus after the algae sloughs from rocks (Murphy et al., 1981). Thus, canopy removal can increase the abundance of invertebrates by enhancing the food quality of detritus.

Density of coho salmon fry often increases during the first 10 to 15 years after timber harvest because of the increased production of invertebrates

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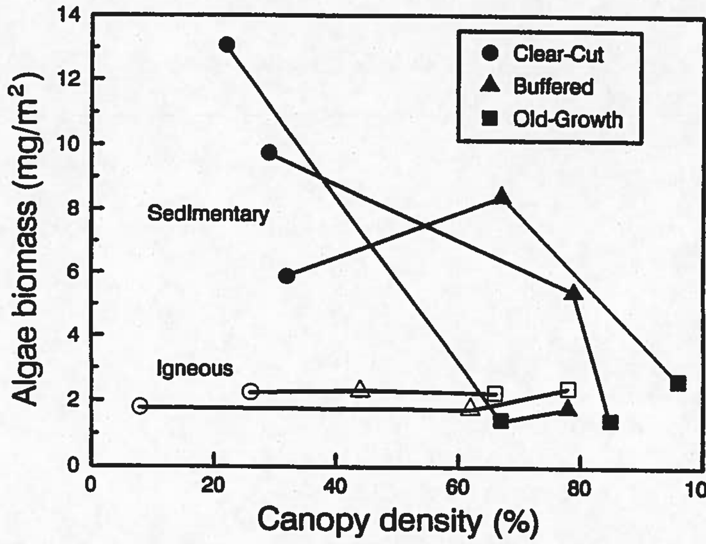


Figure 9.12. Relationship between algae biomass (ash-free dry matter) and canopy density in old-growth, buffered, and clear-cut reaches of streams in five areas of southeast Alaska. Closed symbols indicate areas with sedimentary geologic parent material; open symbols indicate areas with mostly igneous parent material (after Murphy et al., 1986).

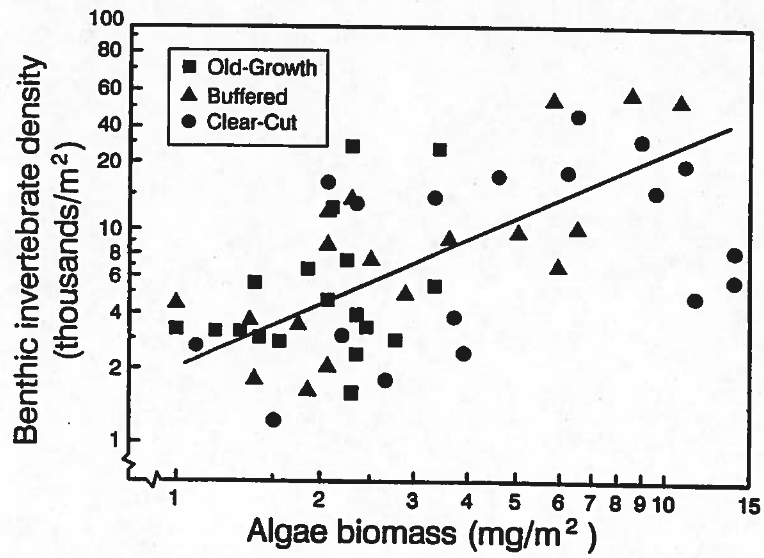


Figure 9.13. Relationship between density of benthic invertebrates and algae biomass (ash-free dry matter) in old-growth, buffered, and clear-cut reaches of streams in southeast Alaska. Both variables are in logarithmic scales. Correlation $r = 0.58$ (after Murphy et al., 1986).

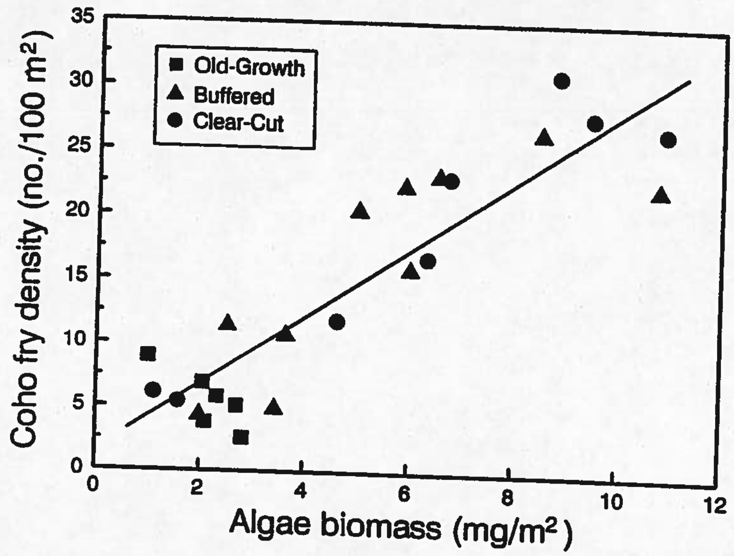
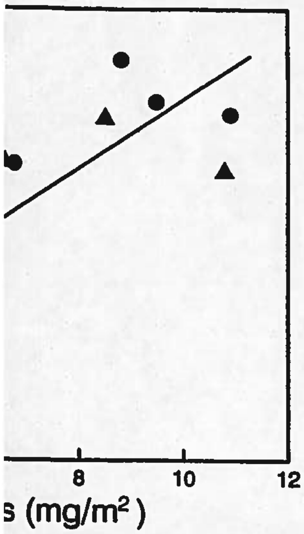


Figure 9.14. Relationship between summer density of coho salmon fry and biomass of algae (ash-free dry matter) in old-growth, buffered, and clear-cut reaches of streams in southeast Alaska. Correlation $r = 0.90$ (after Murphy et al., 1985).

(Murphy and Meehan, 1991). Where food is limiting, the summer density of coho salmon fry can be directly related to the abundance of invertebrates, amount of primary production, or algal biomass (Fig. 9.14). The higher density of coho salmon fry is probably the result of smaller feeding territories (Dill et al., 1981).

On the negative side, timber harvest along small streams may increase stream temperature enough to inhibit growth and cause mortality in juvenile salmonids. In Oregon, although stream temperature reached 30°C, coho salmon and cutthroat trout died only when slash burning quickly raised stream temperature from 13° to 28°C (Hall and Lantz, 1969). In southeast Alaska, however, stream temperature in clear-cuts rarely exceeds 26°C, even on sunny days, except in exposed, intermittent pools (Sheridan and Bloom, 1975). High temperature can also reduce fish growth if food is restricted (Bjornn and Reiser, 1991). However, diel temperature fluctuations simulating conditions in southeast Alaska streams in clear-cuts (maximum range, 6.5° to 20°C) did not influence mortality, growth, or energy reserves of juvenile coho salmon under laboratory conditions (Thomas et al., 1986).

Effects of timber harvest on a stream's physical habitat can also affect summer rearing. High densities of juvenile coho salmon and Dolly Varden are typically associated with LWD and pool habitat (Cardinal, 1980; Dolloff, 1986; Murphy et al., 1986). Loss of LWD can reduce cover and pool



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habitat, as well as reduce the stream channel's storage capacity for organic matter (Bilby and Likens, 1980). Increased fine sediment deposited on the streambed can reduce invertebrate production (Cordone and Kelley, 1961), and turbidity from suspended sediment can reduce primary production (Lloyd et al., 1987) and cause fish to emigrate (Bisson and Bilby, 1982).

Probably most important are the potential long-term effects of overshading from second-growth canopy that may outweigh the increased production in early successional stages (Murphy and Hall, 1981; Sedell and Swanson, 1984). Second-growth vegetation produces a denser shade and lacks the canopy gaps that are common in old-growth forest (Bjornn et al., 1992). Thus, increased stream production in the first 20 years after timber harvest may be followed by 100 years of depressed production (Sedell and Swanson, 1984).

Winter Rearing

Winter habitat, particularly pools with LWD, is critical to the winter survival of juvenile salmonids. Winter mortality, in contrast with summer mortality, appears to result mainly from density-independent factors (Hunt, 1969). Theoretically, carrying capacity of summer habitat sets the upper limit on smolt yield that is then reduced in relation to the severity of winter conditions and quality of winter habitat. Survival factors become more important as latitude increases, because winters are more severe and juvenile salmonids spend more years in freshwater. South of Alaska, most coho salmon spend only one winter in fresh water, but in southeast Alaska two-thirds spend two winters (Gray et al., 1981).

Winter motality in streams is usually substantial: 46 to 94% of summer populations (Hartman et al., 1987; Murphy et al., 1984). Mortality can usually be attributed to hazardous conditions during fall and winter freshets; stranding of fish by ice dams; and physiological stress from low temperature, oxygen depletion, or progressive starvation (Bryant, 1984; Harding, 1993; Murphy et al., 1984; and see Chapter 11). Winter mortality is inversely related to the amount of pool habitat and is usually greater in main stream reaches than in small tributary streams, sloughs, lakes, ponds, and other off-channel areas (Murphy et al., 1984).

Although timber harvest tends to increase fry abundance in summer by opening the canopy, this positive effect can be nullified by reduced winter habitat (Koski et al., 1985). In a study of six southeast Alaska watersheds (Fig. 9.1), summer density of coho salmon fry was significantly greater in both buffered and clear-cut streams than in old-growth streams (Murphy et al., 1986). The enhanced fry abundance in clear-cuts, however, was not maintained through the following winter. Presmolts in late winter were actually less abundant in clear-cuts than in old growth; however, buffered streams maintained higher presmolt density (Thedinga et al., 1989; Fig.

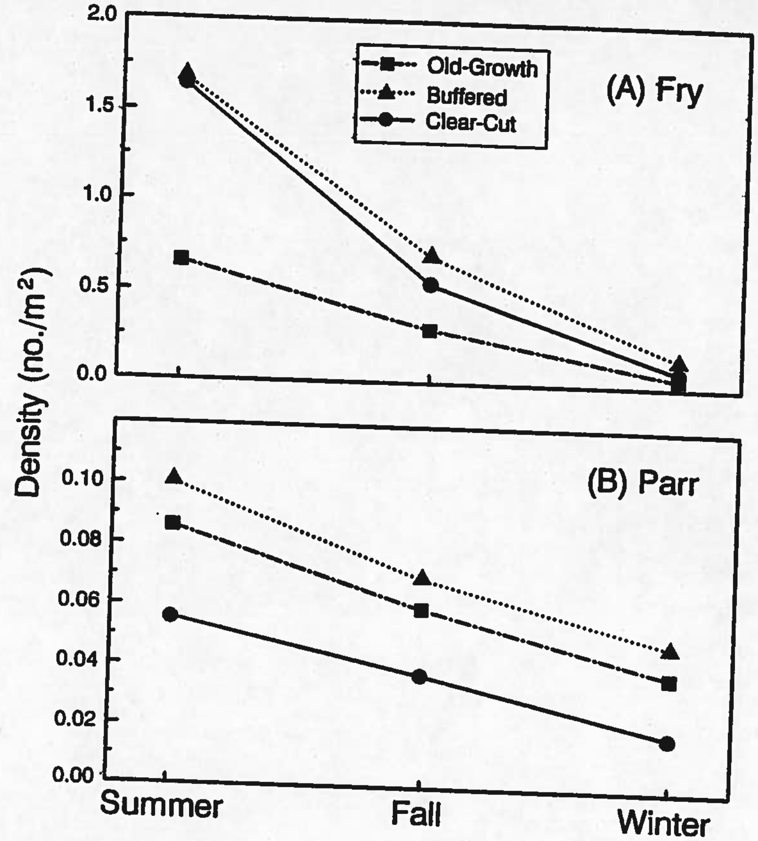
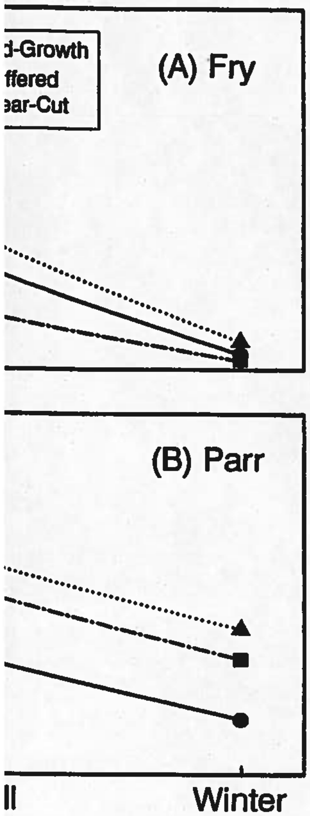


Figure 9.15. Decline in density of coho salmon (**A**) fry (age 0) and (**B**) parr (age 1 and 2) from August 1982 to March 1983 in old-growth, buffered, and clear-cut reaches of streams in southeast Alaska (after Murphy et al., 1985).

9.15). The disadvantage in clear-cuts was a reduction in pools and LWD; the advantage in buffered reaches was a combination of both enhanced food abundance because of more open canopy in summer and increased LWD cover in winter. Thus, winter habitat is frequently a bottleneck in freshwater production of salmon smolts, and timber harvest typically has its most detrimental effects on winter habitat.

LWD is clearly a key habitat feature for juvenile salmonids. It not only provides cover directly, but also forms 80 to 90% of pools in typical valley-bottom streams (Heifetz et al., 1986). LWD also helps maintain water levels in small streams during low-flow periods (Lisle, 1986), which occur in both summer and winter (Lamke et al., 1991). Removal of LWD causes loss of juvenile salmonids (Elliott, 1986).

Fish may travel long distances to suitable winter habitat, paticularly to small tributary streams, spring ponds, lakes, and stream reaches with abun-



(A) fry (age 0) and (B) parr (age 1
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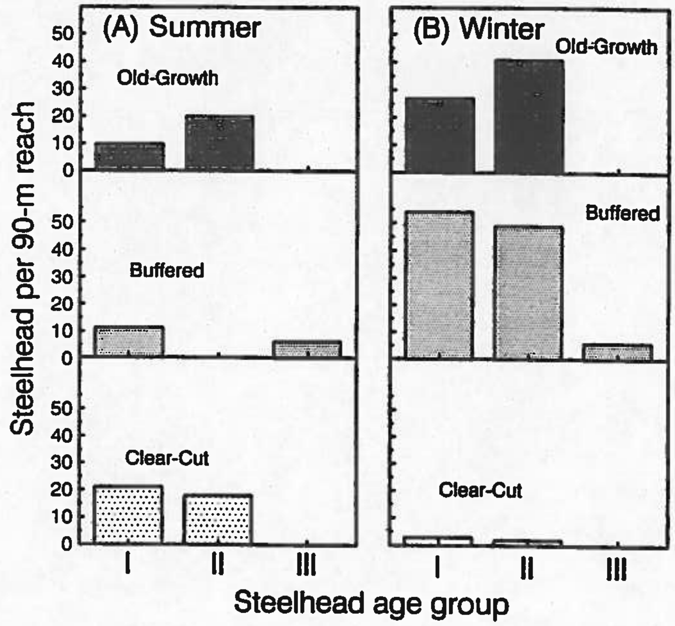


Figure 9.16. Comparison of (**A**) summer and (**B**) winter numbers of juvenile steelhead in old-growth, buffered, and clear-cut reaches of the Shaheen Creek drainage. Each bar shows the total number in three separate 30-m reaches (after Johnson et al., 1986).

dant LWD (Harding, 1993; Murphy et al., 1984). In Shaheen Creek, juvenile steelhead left clear-cut reaches where LWD had been depleted and moved into old-growth and buffered reaches where LWD cover was abundant (Johnson et al., 1986; Fig. 9.16). Logging roads can interfere with juvenile salmonid migrations to winter habitat if stream crossings (i.e., culverts) are not adequately designed and maintained for fish passage.

Blowdown of buffer strips, once considered damaging to habitat, can actually enhance winter cover for juvenile salmonids by providing additional LWD, particularly large trees with attached rootwards (Murphy et al., 1985). In a blowdown area of Shaheen Creek, the number of large pieces of LWD and rootwads more than quadrupled (Fig. 9.17). To our knowledge, no upper limit to the direct relationship between wintering juvenile salmonids and amount of LWD (Fig. 9.18) has yet been measured. In extreme cases of blowdown, however, habitat could be damaged by sediment introduced from upturned rootwads and increased channel instability.

Cumulative Effects of Timber Harvest

Cumulative effects are important considerations in timber harvest because individual harvest units must be considered in the context of all other

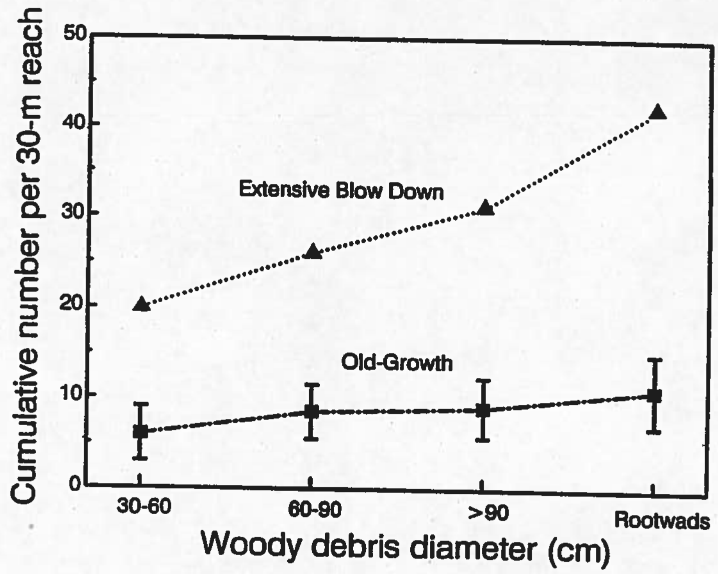


Figure 9.17. Cumulative mean number of pieces of woody debris by diameter size class per 30-m stream length in 18 old-growth reaches and in one buffered reach with extensive blowdown. Vertical bars denote 95% confidence intervals for old-growth (after Murphy et al., 1985).

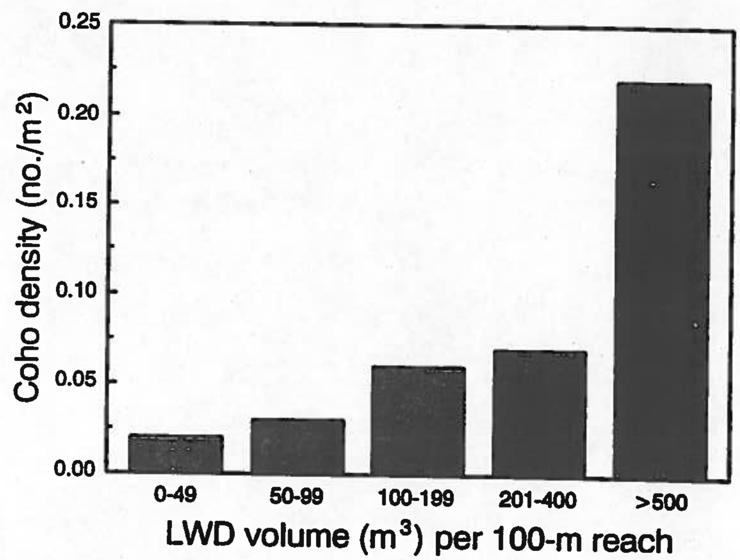
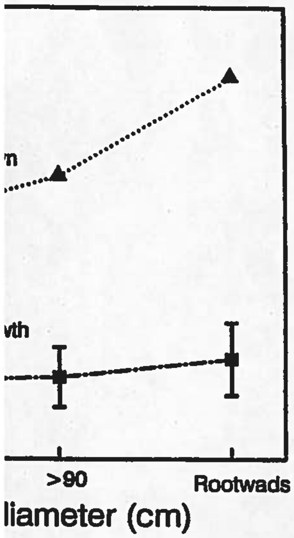


Figure 9.18. The relationship between winter density of coho salmon parr (age 1 and 2) and amount of large woody debris (LWD) (after Murphy et al., 1985).



ɜs of woody debris by diameter size
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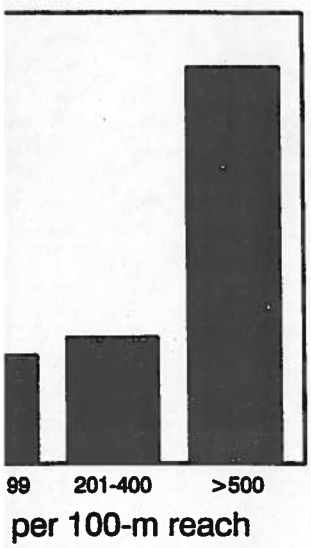

density of coho salmon parr (age 1
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activities in the watershed. Effects of localized small impacts can accumulate and interact, increasing the overall effect on the resource (Burns, 1991). Conventional impact assessments typically are bounded by the expected zone of influence of a single disturbance. Cumulative assessment takes a broader view, with wider boundaries in number of disturbances, geographic area, and time frame (Preston and Bedford, 1990).

Timber harvest effects can accumulate for several reasons. Changes in streamflow, water temperature, and sediment dynamics are not just local problems restricted to a particular stream reach, but problems that can have adverse cumulative effects throughout the entire downstream basin (Sedell and Swanson, 1984). For example, sediment from timber harvest, combined with altered sediment storage and transport due to changed LWD inputs and stability, may cause downstream streambed aggradation, channel widening, and degradation of fish habitat (Smith, 1989).

Wider temporal scales must be considered because habitat variables change systematically as the land and stream recover after timber harvest. Cumulative effects on streamflow, for example, depend on length of time since harvest, because the early decrease in evapotranspiration may be reversed after second-growth vegetation becomes established (Myren and Ellis, 1984). Similarly, the increased primary production after canopy removal can be reversed after second-growth vegetation shades the stream (Bjornn et al., 1992).

Cumulative effects on different habitat variables can also be synergistic or antagonistic. Increased streamflow, for example, may moderate effects of increased stream temperature from canopy removal (Chamberlin et al., 1991). Loss of essential winter cover because of LWD removal can nullify enhanced primary production in summer (Johnson et al., 1986; Murphy et al., 1986).

Identifying cumulative effects of timber harvest on fish habitat is therefore difficult, not only because of the technical complexity, but also because few studies have been sustained over the time required to elucidate the effects (Chamberlin et al., 1991). With the exception of Bryant's (1980, 1985) studies of LWD and channel morphology in Maybeso Creek, no major studies to date have addressed the cumulative effects of forest management on fish habitat in Alaska.

Regulatory Changes to Protect Fish Habitat

Research on the effects of timber harvest on fish habitat has highlighted the critical role of LWD in overwinter survival of juvenile salmonids, the inadequacy of clear-cutting in maintaining LWD, and the effectiveness of buffer strips in protecting fish habitat. The most important problem in streamside management has been how to provide for long-term maintenance of LWD. The best timber stands usually occur close to streams, and this wood is

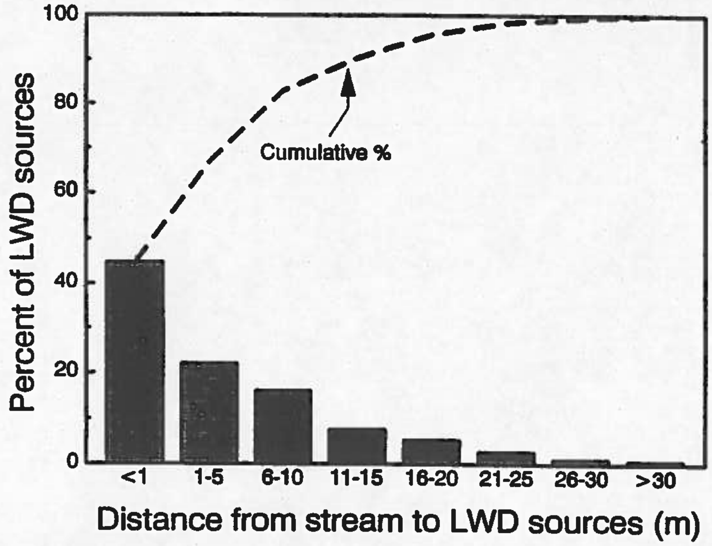
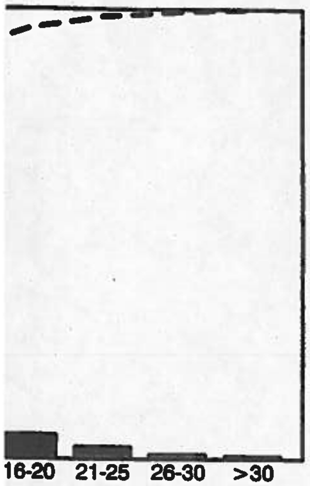


Figure 9.19. Distance from the stream bank to sources of large woody debris (LWD). Histogram bars show percentage of all identified sources ($n = 861$) at given distance from the stream for 32 stream reaches in old-growth forest, southeast Alaska (after Murphy and Koski, 1989).

valuable for both timber harvest and fish habitat. The important questions are how wide should buffer strips be and how many trees should be left along streams to maintain LWD input for the long term.

To establish requirements for buffer strips, studies were undertaken to determine the sources and depletion rate of LWD. Studies in old-growth forest streams showed that 99% of LWD comes from within 30m of the stream channel (Fig. 9.19) through stream undercutting, windthrow, mortality, landslides, and beaver activity (Murphy et al., 1987). By aging saplings growing on LWD, Murphy and Koski (1989) estimated the LWD's age and depletion rate. Longevity of LWD is proportional to bole diameter, increasing from about 100 years for small LWD (10 to 30cm diameter) to over 200 years for very large LWD (>90cm diameter). In most types of streams, LWD is depleted by decay, fragmentation, and export at 1 to 2% per year. A model of the long-term changes in LWD after clear-cutting without buffer strips predicted that LWD would be reduced by 70% at 90 years, and would take more than 250 years to recover (Fig. 9.20). This model made a strong case for the need for minimum 30-m buffer strips along streams to maintain LWD.

Based on this research, the National Marine Fisheries Service, Alaska Region, issued a policy statement in 1988 calling for minimum 30-m buffer strips along anadromous fish streams. This policy became the focal point for



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habitat. The important questions
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r the long term.
trips, studies were undertaken to
ɛ of LWD. Studies in old-growth
Ͻ comes from within 30 m of the
n undercutting, windthrow, mor-
ırphy et al., 1987). By aging sap-
i (1989) estimated the LWD's age
.s proportional to bole diameter,
l LWD (10 to 30 cm diameter) to
)cm diameter). In most types of
nentation, and export at 1 to 2%
nges in LWD after clear-cutting
ı would be reduced by 70% at 90
ears to recover (Fig. 9.20). This
for minimum 30-m buffer strips

Marine Fisheries Service, Alaska
calling for minimum 30-m buffer
; policy became the focal point for

debate as the Congress and the Alaska Legislature considered reforming forest practices on Federal, State, and private lands.

Congress passed the Tongass Timber Reform Act (Public Law 101-626) in November 1990, reforming timber harvest practices on federal lands in the Tongass National Forest. The Act requires no-cut buffer strips at least 30 m wide on both sides of all class I streams (those with anadromous fish) and on those class II streams (those with resident fish only) that flow directly into a class I stream. No buffer strips are required along class III streams (those with no fish), but BMPs must be followed to prevent downstream sedimentation and excessive increases in temperature.

The Alaska Legislature amended the Alaska Forest Resources and Practices Act (AS41.17) in May 1990 to reform forest practices on State and private lands. The new standards differ between State and private lands. On State lands, timber harvest is prohibited within 30 m of anadromous fish streams; on private lands, standards differ according to stream type:

1. along a "type A" stream (anadromous fish stream not incised in bedrock), no timber may be harvested within 22 m of the stream bank;

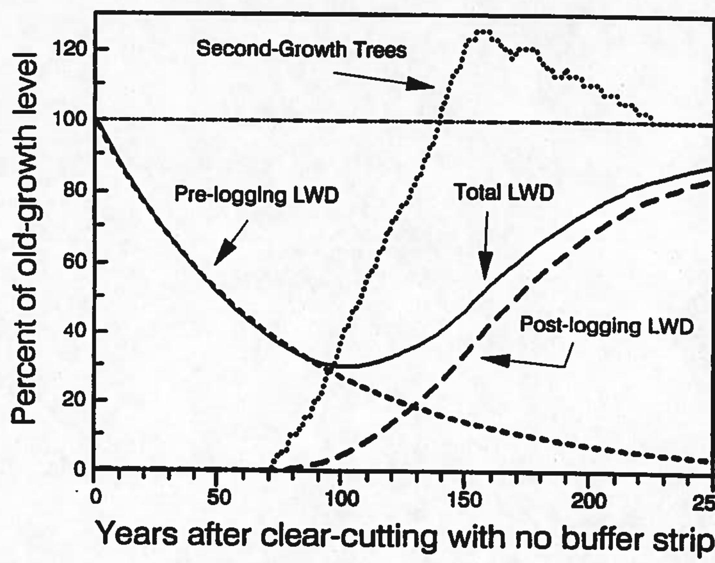

Figure 9.20. A model of changes in number of key pieces of large woody debris (LWD, >60 cm diameter) in a small valley-bottom stream channel after clear-cutting without a buffer strip. The model predicts the amount of LWD as a percentage of old-growth levels, based on estimates of the depletion rate of prelogging LWD, regrowth of streamside trees, and input of LWD from second-growth forest. Total LWD equals the sum of pre- and postlogging LWD (after Murphy and Koski, 1989).

2. along a "type B" stream (anadromous fish stream incised in bedrock), timber harvest within 30m of the stream or to the slope break must comply with BMPs; and
3. along a "type C" stream (small tributary without anadromous fish), timber harvest within 15m of the stream or to the slope break must comply with BMPs.

The Alaska Forest Resources and Practices Act grants variations from requirements in some cases. A landowner may propose a variation to the State Forester. The Department of Fish and Game has due deference in such requests concerning fish and wildlife habitat. There is also an automatic variation granted on small streams less than 1.5m wide, which allows the landowner to harvest up to 25% of the trees within the area between 7.6 and 22m of the stream.

These new laws enacted in 1990 substantially improved the protection of salmonid habitat in Alaska. Further research, however, is needed to assess effectiveness of BMPs in preventing downstream cumulative effects of timber harvest along small tributaries and in preventing sedimentation from construction and use of logging roads.

Summary

The interaction between timber and fisheries in Alaska has been evolving since the 1950s. Early research, focusing on spawning habitat, determined habitat requirements and mortality factors that timber harvest can affect, but impacts on salmon were not demonstrated. As awareness grew of possible impacts to salmon rearing habitat, timber and fisheries groups joined together to form the Alaska Working Group on Cooperative Forestry–Fisheries Research to foster research on priority issues. This research identified LWD as the most important variable in the timber–fisheries interaction in southeast Alaska, being both easily affected by timber harvest and critical for salmonid rearing habitat. Buffer strips were found to be effective in providing long-term sources of LWD after timber harvest. Consensus and compromise led to legislation in 1990 requiring buffer strips along anadromous fish streams on public and private lands. These laws provided the highest level of protection for anadromous fish habitat of any state.

The interaction between timber and fisheries continues today as land managers and regulators apply the new regulations in the field and monitor their effectiveness. Research continues to be needed to evaluate and refine BMPs and determine their applicability to other regions of Alaska where the functional role of LWD and other habitat variables in salmonid population dynamics may be different from that in southeast Alaska.

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