John D. Stednick
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Hydrological and Biological Responses to Forest Practices

The Alsea Watershed Study

Foreword by George W. Brown and James T. Krygier

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Chapter 15
The Alsea Watershed Study: A Comparison with Other Multi-year Investigations in the Pacific Northwest

Peter A. Bisson, Stanley V. Gregory, Thomas E. Nickelson, and James D. Hall

The Alsea Watershed Study (AWS) was the first long-term fisheries research project to address the effects of forestry operations on salmonid populations in the Pacific Northwest using a watershed approach. To this day it remains one of a very limited number of investigations that have provided long-term information on salmon and trout responses to forestry operations. These studies have had a significant impact on the development of state and provincial forest practices regulations. The initial results of the AWS, which demonstrated negative impacts of logging on salmonid spawning and rearing (Hall and Lantz 1969), contributed to some of the first laws regulating forestry operations adjacent to small streams.

Over the past several decades, different study designs have been used to evaluate the effects of forest management activities in Pacific Northwest streams. The first type of study has involved intensive, long-term evaluations of experimentally applied forestry operations within a single area. This has been the approach used in both the AWS (Hall et al. 1987) and the Carnation Creek watershed study (Hartman and Scrivener 1990) in British Columbia. The AWS examined experimentally controlled timber harvest in three small adjacent watersheds, with multi-year pre and posttreatment evaluation periods. In the Carnation Creek watershed study, harvest treatments were applied along different reaches of one stream rather than in adjacent watersheds. However, the pre and posttreatment monitoring approach was generally similar to the AWS (Hartman and Scrivener 1990). In each of these studies, treatments were not replicated in other watersheds.

Using a second type of study design, other investigators followed stream recovery after forest management had already occurred, with nearby unmanaged watersheds or stream reaches acting as control sites. In most studies there was little or no pretreatment sampling and the treatments themselves were not

Peter A. Bisson
USDA Forest Service, Pacific Northwest Research Station, Olympia, WA 98512-9193
pbisson@fs.fed.us

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applied to several watersheds. Such an approach was used in the Clearwater Rivenbasin of Washington's Olympic Peninsula (Cederholm and Reid 1987). A third design has involved substituting spatial replication (multiple sites) for temporal replication (multiple years) by employing geographically extensive surveys of streams whose watersheds have undergone forestry operations or forestry-related disturbances over similar time periods (Murphy and Hall 1981; Murphy et al. 1981; Hawkins et al. 1983; Bisson and Sedell 1984).

Each of the three approaches has usually involved some type of control or reference condition such as an unmanaged watershed, upstream undisturbed stream reach, or pretreatment sampling period. Few studies, however, have attempted to replicate experimental treatments among different streams in a preplanned manner, i.e., where replication of treatments at different sites has been systematically included in hypothesis testing. Given the considerable interest in experimental design of ecological studies (e.g., Hurlburt 1984; Walters et al. 1988, 1989) lack of replication has limited our ability to extrapolate results from these studies to other watersheds in the region or to separate treatment effects from concurrent extraneous factors such as climate cycles. Effects attributable to forest management apply only to those reaches or watersheds measured and only during the period in which they were studied.

Although both the Alsea Watershed and Carnation Creek studies lasted more than 15 years, the majority of postdisturbance monitoring studies and extensive surveys lasted less than ten years, and many have taken place over intervals of only a year or two. Most examinations of streams and their fish populations have occurred from the 1970s to 1990s (Hicks et al. 1991b), but there has been little temporal overlap among studies within Pacific Northwest ecoregions, and this time interval has witnessed significant climate and oceanic change (Francis and Sibley 1991; Pearcy 1992; Beamish and Bouillon 1993). Investigations of the impacts of forestry practices on salmonid populations in coastal and western Cascade watersheds of the Pacific Northwest have thus differed in approach, in geographical location, and over time periods when climate was changing. Perhaps it is not surprising, therefore, that consistent and unequivocal conclusions concerning the impacts of forest management on fish populations in Pacific Northwest streams have failed to emerge (Hicks et al. 1991b; Bisson et al. 1992).

Other multi-year fish population studies in the region have attempted to evaluate salmonid restoration and enhancement projects (Everest et al. 1984; Johnston et al. 1990; Ward and Slaney 1993) or supplementation of wild populations with hatchery-produced fry (Nickelson et al. 1986). These studies have often been carried out in watersheds where some logging has occurred, but the primary intent of the investigations has not been to examine forestry-related impacts. Nevertheless, such studies constitute another source of long-term salmonid population data for the region. Syntheses of the results of multi-year investigations of salmonids (Lichatowich and Cramer 1979; Elliott 1985, 1994; Hall et al. 1987; Hartman and Scrivener 1990; Hilborn and Winton 1993) have shown that considerable interannual variation in population abundance is

commonplace and that high levels of natural variability pose an obstacle to understanding how anthropogenic disturbances or other management activities affect fish.

The objective of this paper is to compare results of the AWS with other multi-year watershed investigations in the Pacific Northwest. In particular, we address the question of how much interannual variation exists in the abundance of stream-dwelling salmonids and the extent to which this variation limits our ability to detect population responses to forestry-related disturbances and other management activities. Comparisons are limited to studies of 5 or more consecutive years duration, conducted in coastal or Cascade Mountain streams during the period of summer low flow, when populations tend to reflect summer carrying capacities (Fransen et al. 1993). Information on the variability of adult brood-year escapement and smolt production is also used where available. We further limited comparisons to small and mid-sized watersheds with either non-migratory trout or a combination of resident and anadromous salmonids, as these circumstances most closely resemble those of the AWS. We conclude with a discussion of the importance of long-term research projects like the AWS, and the importance of identifying fish population measures that are especially sensitive to management activities.

Alsea Watershed and Forest Practices

Within the states of Oregon and Washington the pattern of forest land ownership is mixed, but federally owned lands occupy the overall majority of forest area in the region. State-owned and private commercial forest lands make up a lower overall percentage of coastal and west slope Cascade Mountain forests but tend to dominate coastal river basins from central Oregon to the west coast of Washington's Olympic Peninsula (Pease 1993). Federal forestry practices have been regulated by regional operating guidelines of the USDA Forest Service and the USDI Bureau of Land Management, while state and private forestry practices have been regulated by an evolving set of state forest practice regulations that were initiated in the early 1970s.

Environmental protection standards applied to state and private forest lands have differed somewhat from those applied to federal lands over the previous decades. In general, watersheds within state and private ownerships have greater percentages of recent timber harvest, higher road densities, and narrower buffer strips along fish-bearing streams than watersheds within predominantly federal ownership, due in part to designated wilderness or research natural areas in federal forests and to stricter federal environmental guidelines (Thomas 1993). The AWS, which involved three small watersheds with mixed federal and private industrial ownership, included one site (Needle Branch) that was logged and burned without streamside protection and another site (Deer Creek) that was patchcut and included streamside buffers. A third watershed (Flynn Creek)

served as the control. Although it is tempting to extrapolate the Needle Branch results to logging impacts in state and private forests and the Deer Creek results to federal forests, such extrapolation would probably not be valid. Needle Branch was treated in a manner more severe than would currently be permitted under any set of regulations, although similar treatments did occur in other small watersheds on private forest land at the time it was logged. The pattern of patchcutting and buffer strips in the Deer Creek watershed may now be found in most types of forest ownership. No attempts have been made to distinguish ownership type in our comparisons. Different locations have had different natural disturbance histories, varying logging practices, and sometimes other land uses such as agriculture and grazing. Thus it is virtually impossible to relate habitat conditions and fish populations to specific disturbance events, whether natural or anthropogenic. Unless the watershed has been designated as a wilderness area or a late-successional forest reserve, we assumed that every site has experienced some changes from forestry operations.

Study Locations, Objectives, and Methods

Locations and dates of multi-year salmonid population studies selected for comparison of interannual variation are in Table 15.1. Study sites were scattered along the Pacific Northwest coast from the northern end of Vancouver Island to the Coos River system in southwestern Oregon (Fig. 15.1). Most studies selected for comparison with the Alsea watershed were located in coastal drainages and contained anadromous salmonids. A few sites (McKenzie River tributaries, Fish Creek, Huckleberry Creek) were located in the Cascade Mountains. These sites tended to be of higher elevation than the coastal sites, but still had primarily rainfall-dominated hydrologic regimes. The two McKenzie River tributaries (Mack Creek and Johnson Creek) did not contain anadromous salmonids, although juvenile Chinook salmon *(Oncorhynchus tshawytscha)* were occasionally found near the mouth of Johnson Creek.

Most study sites contained populations of coho salmon *(0. kisutch),* steelhead *(0. mykiss),* and coastal cutthroat trout *(0. clarkii clarkii).* Investigators usually made no attempt to distinguish anadromous from resident cutthroat trout, and juvenile rainbow trout were normally assumed to be anadromous steelhead. Objectives of individual studies sometimes limited evaluations to certain species (e.g., Nickelson et al. 1986). We found the majority of long-term investigations, i.e., those with 5 or more consecutive years of population data, were concerned with salmonid enhancement, including fry supplementation (Nickelson et al. 1986) and habitat restoration (Bilby unpublished; Reeves et al. 1990; Ward and Slaney 1993). Most sites also contained a variety of non-salmonid fishes, especially cottids and cyprinids, but their abundances were rarely reported. Several of the studies were ongoing and have not been published as technical reports or papers in scientific journals

Table 15.1 Long-term salmonid population study sites in Pacific Northwest watersheds used in this comparison. Those without superscript indicate coho, steelhead, and cutthroat trout.

State/ ProvinceRiver basin/Watershed Stream	Species	Years of study	Adults	Summer juveniles	Smolts	Source(s)
Oregon						
Alsea Watershed Study	Coho, cutthroat	1959–1974; 1988–1996				Chapter 5; Chapter 14
Flynn Creek			x[1]	x	x[1]	
Deer Creek			x[1]	x	x[1]	
Needle Branch			x[1]	x	x[1]	
Oregon coastal streams	Coho	1980–1985				Nickelson et al. (1986)
Siuslaw River						
Panther Creek			x	x		
Rogers Creek			x	x		
Misery Creek			x	x		
Doe Creek			x	x		
Dogwood Creek			x	x		
Billie Creek			x	x		
Beaver Creek						
No. Fk. Beaver Creek			x	x		
Alsea River						
Horse Creek			x	x		
Drift Creek			x	x		
Yaquina River						
Hayes Creek			x	x		
Salmon Creek			x	x		
Deer Creek			x	x		
Neskowin Creek			x	x		
Little Nestucca River						
Louie-Baxter Creek			x	x		
Bear Creek			x	x		
Oregon coastal streams	Coho	1988–1993				T.E. Nickelson (unpublished)
Alsea River						
East Fork Lobster Creek				x	x	
Upper Lobster Creek				x	x	
Nestucca River						
East Fork Creek				x	x	
Moon Creek				x	x	

(continued)

Table 15.1 (continued)

State/ ProvinceRiver basin/Watershed Stream	Species	Years of study	Adults	Summer juveniles	Smolts	Source(s)
Clackamas River (Cascades)	Steelhead, coho	1983–1990				Reeves et al. (1990)
Fish Creek			x	x	x	
McKenzie River (Cascades)						
Mack Creek	Cutthroat	1973–1996		x		S.V. Gregory (unpublished)
Johnson Creek	Cutthroat	1987–1992		x		P.A. Bisson (unpublished)
Coos River (Coast Range)						
Lost Creek	Steelhead	1986–1993		x		R.E. Bilby (unpublished)
Washington						
Olympic Peninsula streams	Steelhead, coho,					Johnson and Cooper (1986)
Siebert Creek	sea-run	1981–1986	x[2]		x	
McDonald Creek	cutthroat		x[2]		x	
Deschutes River						
Huckleberry Creek	Coho	1986–1992	x	x		Washington Dept. Fish & Wildlife and P. A. Bisson (unpublished)
British Columbia						
Vancouver Island						
Carnation Creek	Coho, steelhead	1970–1987	x	x	x	Hartman and Scrivener (1990)
Keogh River	Steelhead	1976–1982	x	x	x	Ward and Slaney (1993)

[1]coho salmon
[2]steelhead

(Table 15.1). Although their methods and results have not been peer-reviewed, the number of unpublished studies constituted a significant fraction of the long-term studies in the region, so they have been included in our comparison.

Objectives of the studies, as noted earlier, generally related either to the effects of logging on fish populations or to productivity enhancement through fry supplementation or creation of habitat. In the latter case we excluded study sites in which hatchery fish had been planted, but included unstocked control streams (Nickelson

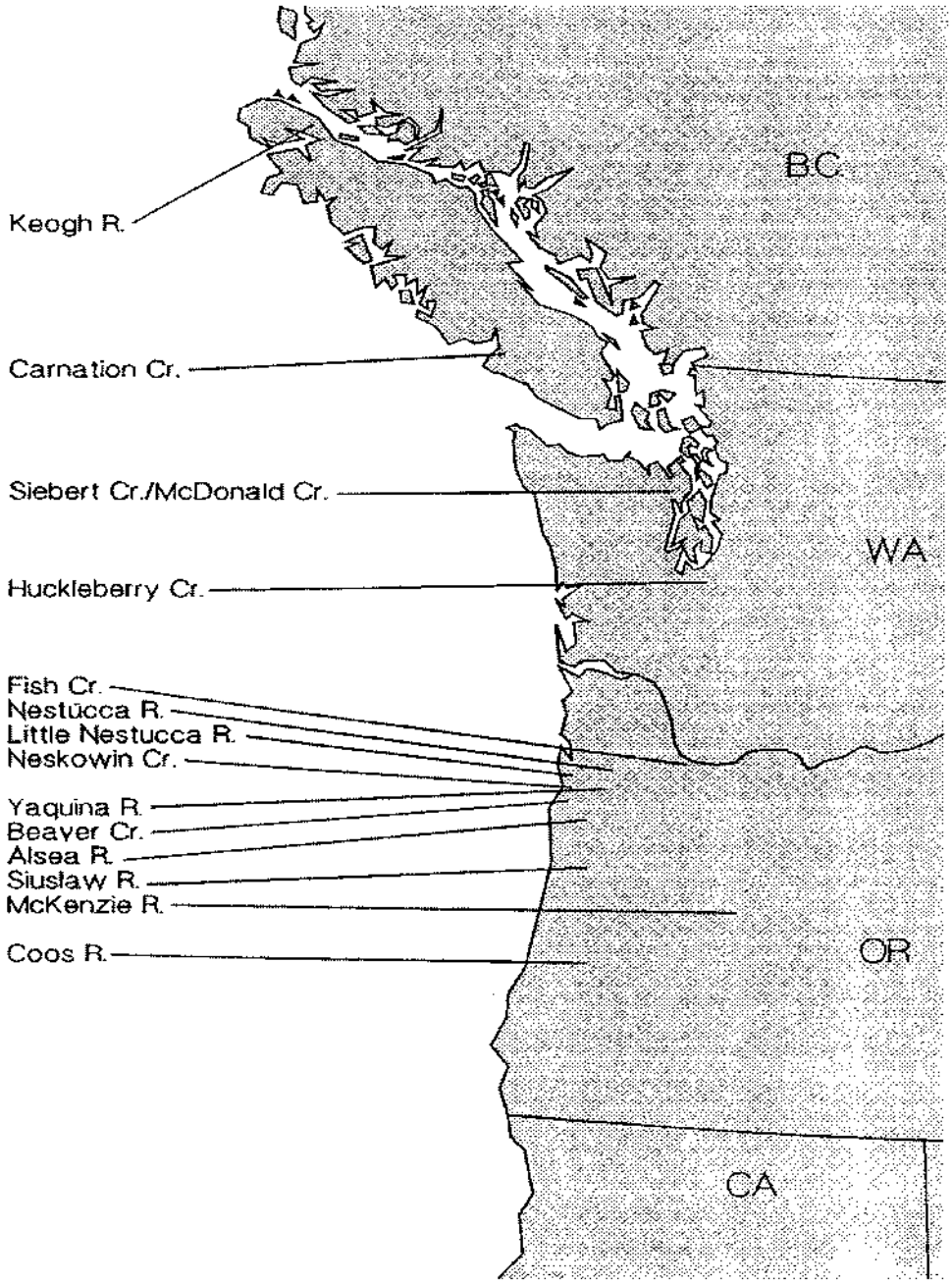

Fig. 15.1 Location of multi-year studies of salmon populations in the Pacific Northwest that were used in the comparison

et al. 1986). To be considered for comparison we required that studies (1) included quantitative estimates of salmonid abundance during the period of summer low flow, (2) had been sampled at least 5 consecutive years, (3) used similar sampling methods (but not snorkeling) from year to year, (4) possessed information on at least one of the following species: coho salmon, steelhead, or cutthroat trout, and (5) had taken place in small or mid-size watersheds (2nd–5th order) over the same time period as the AWS, i.e., 1959–1996.

In most studies, including the AWS, fish populations were censused by mark-recapture, multiple-pass electrofishing, or seining. Actual measures of abundance, however, often differed. Some investigators reported density as numbers per unit of stream area (no. m^{-2}); others chose numbers per unit of channel length (no. $100m^{-1}$) while still others presented estimates of the total population inhabiting the streams based on stratified sampling of representative habitat types. Differences in the method of reporting fish abundance made density comparisons among study sites difficult, because it was usually not possible to convert each estimate to a common density measure. Thus we were not able to determine whether the absolute abundance of salmonids in Alsea Watershed streams departed significantly from results of some of the other long-term investigations. However, it was possible to compare the interannual coefficients of variation [(standard deviation/mean)• 100] in salmonid density among all sites. Interannual coefficient of variation (CV) is a statistic describing the relative variation in population abundance from year to year, independent of the absolute magnitude of the density estimates. Likewise, we compared the CV of adult spawners and smolts among sites where these data were available. Because the relationship between numbers of brood-year adults and juvenile progeny was relevant to the question of whether variation in numbers of rearing juveniles was influenced primarily by rearing conditions or adult escapement, we plotted trends in these parameters over time.

A total of 11 multi-year fisheries studies from the Pacific Northwest were compared (Table 15.1), about half of which were still in progress at the time this paper was written or unpublished and are therefore not reviewed here in detail. In only four studies (Alsea Watershed, Fish Creek, Carnation Creek, Keogh River) were migrating adults, juveniles, and smolts concurrently censused. Other investigations monitored either adults and juveniles or juveniles and smolts.

Comparison of Study Results

Studies of Logging Effects

Detailed findings of the AWS are given in Chapters 5 and 14, and are also discussed by Hall and Lantz (1969), Moring and Lantz (1975), and Hall et al. (1987). Populations of both juvenile coho salmon and cutthroat trout were monitored from 1959 until the early 1970s (cutthroat trout were not censused until 1962) and again from 1988 through 1996. Densities have been highly variable in all three watersheds over these intervals (Fig. 15.2), and inferences about the effects of logging on salmonid abundance have been somewhat difficult to draw. The cutthroat trout population in Needle Branch, the clearcut watershed, was depressed after logging (Hall et al. 1987), but densities of

cutthroat trout (all age groups combined) in the late 1980s and early 1990s were comparable to prelogging levels during most years. However, densities of trout age 1 and older were even further depressed than they had been immediately after logging (See Chapter 14). Flow in lower Needle Branch had always been low in late summer during the original AWS, with the stream flowing subsurface between pools. However, in 1988 and 1992 the flow was exceptionally low; in late summer the stream was reduced to one or only very few isolated pools. During these 2 years few or no salmon or trout were present (Fig. 15.2). The cause of the recent increase in intermittency of Needle Branch in summer is not known, but may be related in some way to the history of forest operations. The summer low flow of a stream that had been clearcut in the Oregon Cascades dropped below prelogging values during the period 10-25 years after logging (Hicks et al. 1991a). Vigorous regrowth of riparian vegetation was suggested as the cause for reduced summer flow in that watershed.

Production of coho salmon smolts declined in each stream, including the unlogged control, during the early post-logging period (1967-73) relative to the prelogging period (1959-66) (See Chapter 5). The numbers of adult salmon returning to the streams (Fig. 15.3) were quite variable over both the pre- and post-logging periods, but the averages after logging were similar to the prelogging values in all three streams. Although the correlation between the number of brood-year females and summer fry densities was not strong, the density of juvenile coho salmon in the AWS sites did seem to be influenced by low spawner escapement (Fig. 15.3); low summer fry densities followed from years of unusually poor adult escapement. Hall et al. (1987) computed the total production of migrant fry per spawning female to provide an index of survival from egg to emergence. They found that abundance of migrant fry in Needle Branch declined after logging, but did not decline significantly in either the patchcut or control watersheds (Fig. 15.4). This observation suggested that survival of coho salmon during emergence and in early post-emergent environments was reduced after logging in the Needle Branch watershed.

The Carnation Creek study documented a number of physical and biological changes to the watershed after timber harvest and silvicultural treatments that included slash burning and herbicide application (Table 15.2). Increases in solar radiation striking the stream surface, summer and winter water temperatures, nutrient levels, water yield from small tributaries (but not from the mainstem of Carnation Creek), channel erosion, and fine sediment concentrations in spawning areas were documented after logging, burning, and herbicide treatments. Overall reductions were found in both large and small woody debris, as well as litter inputs, and the biota of Carnation Creek was generally reduced and more variable after timber harvest (Hartman and Scrivener 1990). Macroinvertebrates declined by almost half. Coho salmon declined slightly (although there were both positive and negative effects of logging on survival and growth of juveniles), chum salmon declined significantly (although much of the decline was caused by

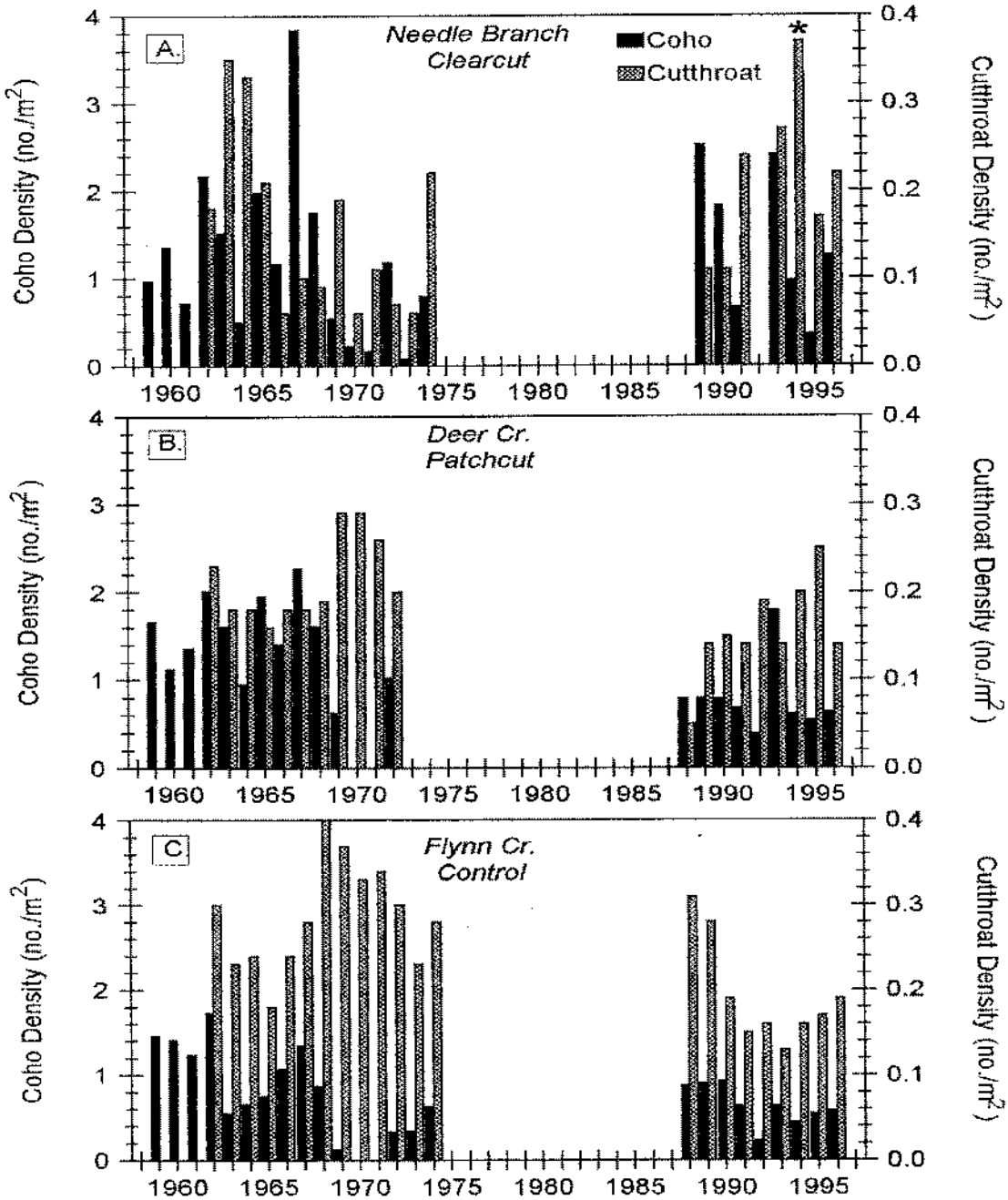

Fig. 15.2 Density (no. m^{-2}) of coho salmon and cutthroat trout during late summer (August–September) in the three Alsea Watershed streams. Data from Chapter 14. Asterisk denotes that trout density for Needle Branch in 1994 was 1.14 fish per m^2 (94% age 0)

poor ocean conditions), the steelhead population decreased, and cutthroat trout were largely unchanged (combined trout are shown in Fig. 15.5a).

Escapement of adult coho salmon to Carnation Creek dropped sharply in the late 1980s (Fig. 15.5b), raising the possibility that reduced numbers of juveniles may have been caused primarily by oceanic factors unrelated to

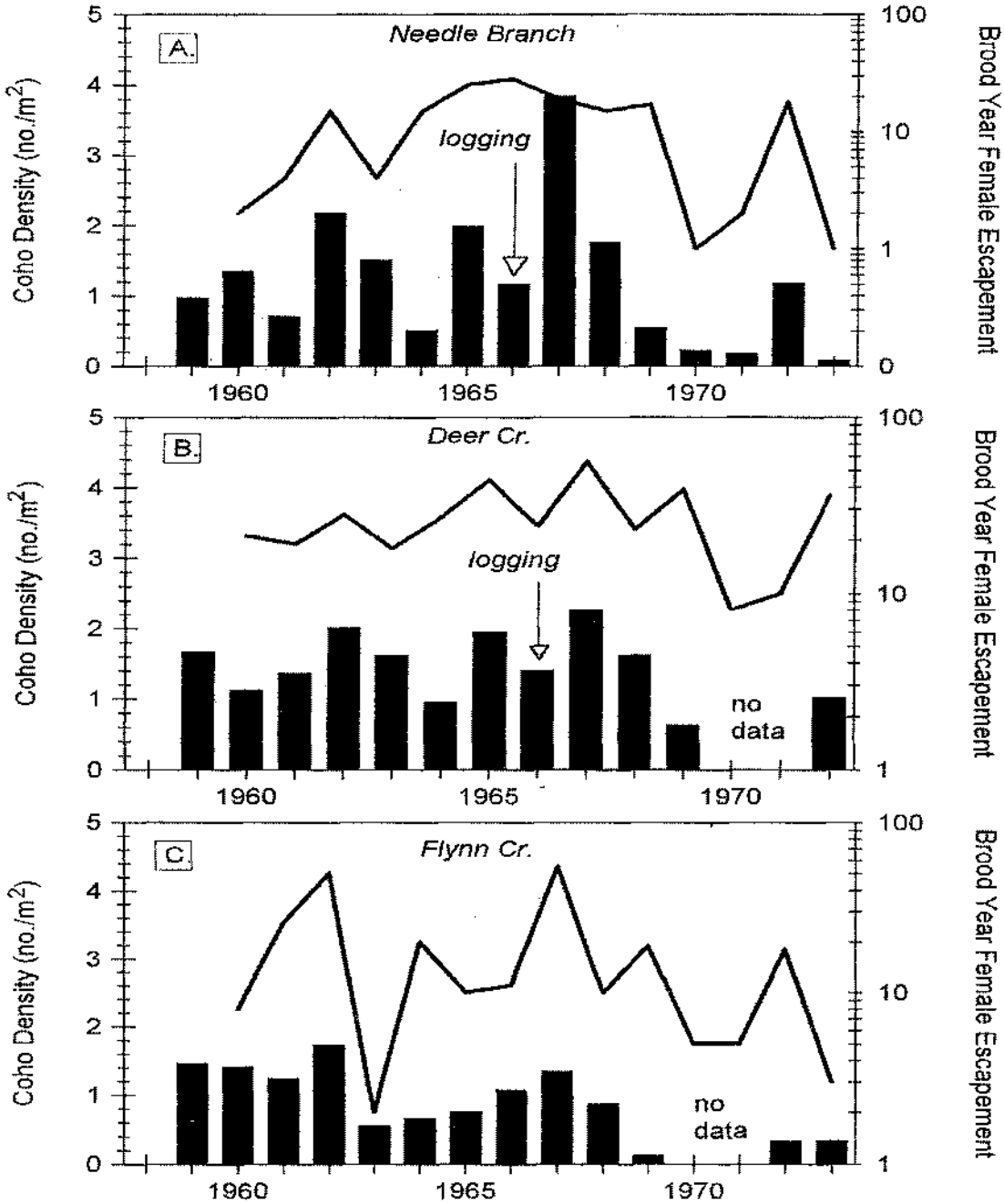

Fig. 15.3 Summer densities of juvenile coho salmon (bars) and escapement of brood-year females (line) to each of the AWS streams from 1959 to 1972. Data from Chapter 5

logging effects. Using data from the Carnation Creek study, we calculated the number of downstream migrant fry produced per spawning female before, during, and after logging in order provide an index of survival to emergence to compare with the results from the AWS. Declines in numbers of migrant fry per adult female in Carnation Creek during and after logging (Fig. 15.4d) were remarkably similar to the reduction in migrant fry observed after

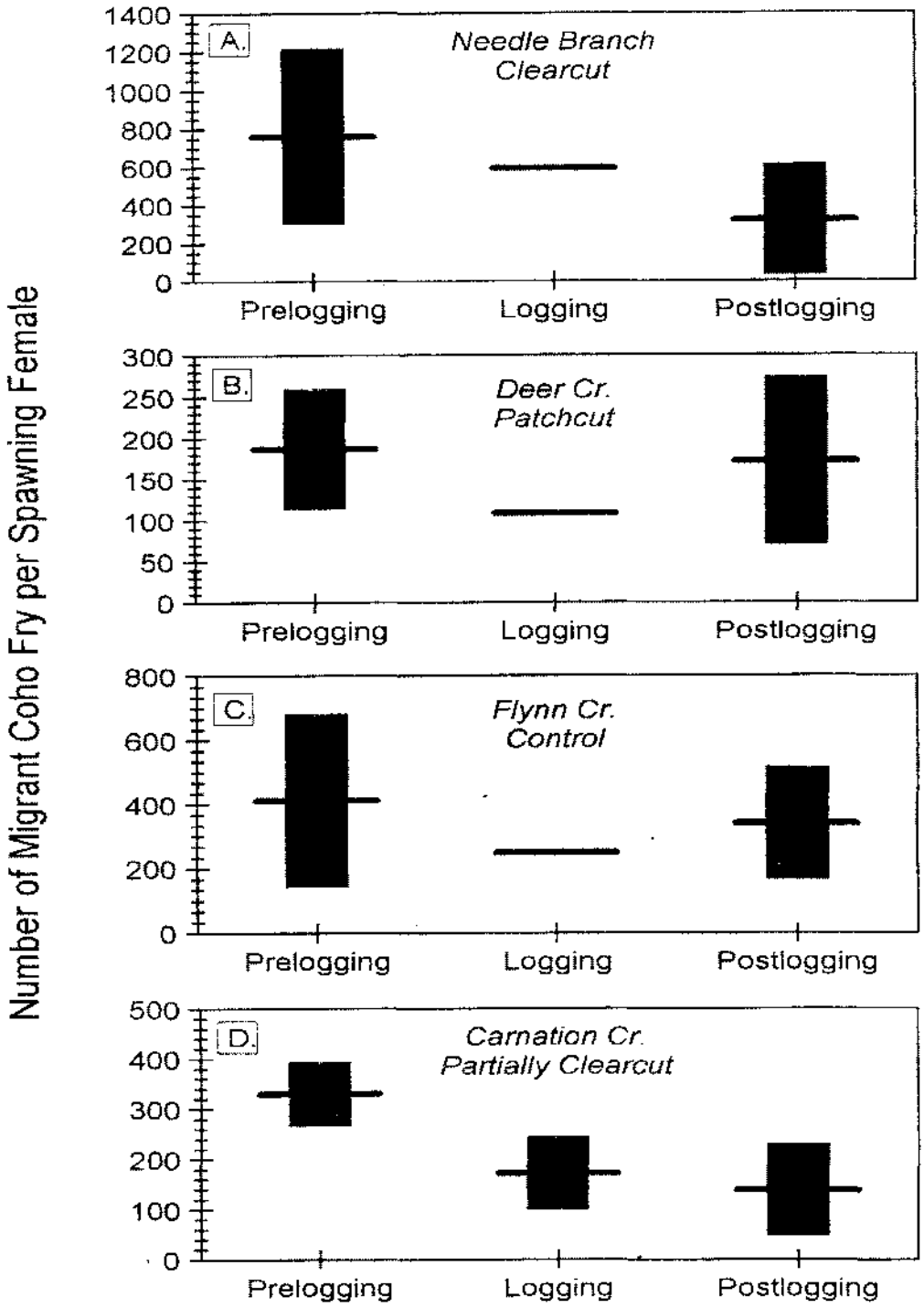

Fig. 15.4 Number of migrant coho salmon fry produced per spawning female (mean ± 1 SD) in the AWS streams and Carnation Creek before, during, and after logging. Note differences in the scale of the vertical axis for each graph. Data from Chapter 5 and Hartman and Scrivener (1990)

logging in Needle Branch (Fig. 15.4a); both streams exhibited a reduction of about 60%. However, the actual number of migrant fry per female was about twofold greater in Needle Branch than in Carnation Creek. It is possible that

Table 15.2 Summary of physical and biological changes in the Carnation Creek watershed after timber harvest and silvicultural treatments. Biological changes (right column) were likely related to a combination of the physical changes in the left column. From Hartman and Scrivener (1990, pages 124-125)

Physical changes	Biological changes
Light intensity on the stream surface doubled or more than doubled following logging.	Macroinvertebrate densities were reduced 40-50% following streamside logging and silvicultural treatments.
Diurnal and seasonal variability of stream temperature increased. Mean temperatures were 3°C higher during summer and 0.5°C higher during winter for the first decade following logging.	Coho salmon egg-to-fry survival, numbers of age-0 fish in autumn, and numbers of 2-yr-old smolts declined after logging; fry emerged earlier producing a longer period for growth and a larger size for parr; numbers of age-1 smolts and female adults increased then decreased at double the prelogging interannual variability.
Nutrient levels increased 40-80%, at least during high flows, for 2-4 yr following logging and for 1-2 yr following herbicide application.	
Water yield increases were detected in tributary watersheds >95% clearcut, but they were not significant for the total basin (41 % clearcut). Groundwater levels increased in the floodplain. Duration of the period of higher groundwater levels was at least a decade.	Chum salmon egg-to-fry survival, fry size, and adult returns were reduced and more variable following logging and the fry emigrated earlier to the ocean. The 90% reduction of adult chum salmon was caused by poor ocean conditions (64%) and by logging (26%).
Fine woody debris increased in the stream, but it was lost within 2 yr.	The steelhead population decreased following logging.
Large woody debris became more clumped, and it was reduced to ~30% of prelogging volume within 2 yr in areas that were logged to the stream bank. Stability and piece size of large woody debris decreased within 2 yr. Instability of large woody debris continued for at least a decade.	The cutthroat trout population was unchanged following logging.
Channel erosion and change in channel location began within 4 yr of the onset of logging and continued throughout the study.	
Litter input to the stream was reduced to 25-50% of prelogging levels after logging and silvicultural treatments. About half of this loss had recovered within a decade.	
Pea gravel and sand content of the streambed doubled during the decade since logging and continued to change throughout the study.	

the number of fry per female was influenced by watershed area in some way. Fewer fry were produced per female from the largest watersheds—Carnation Creek and Deer Creek—than from the two smaller watersheds—Flynn Creek and Needle Branch. The mechanisms causing this apparently significant difference in fry per female between watersheds of different sizes are not

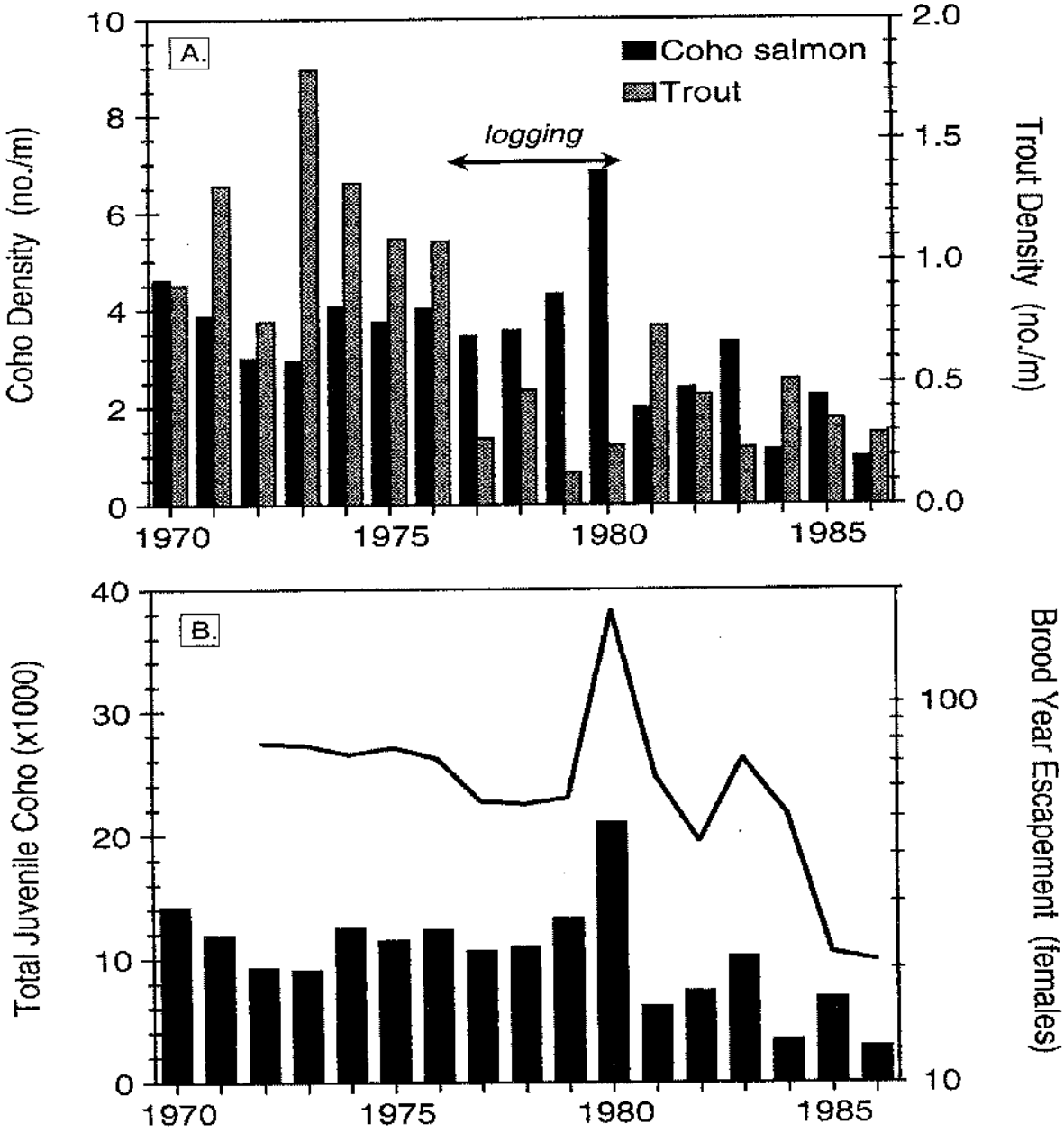

Fig. 15.5 (a) Density of coho salmon and "trout" (both steelhead and cutthroat trout) in Carnation Creek from 1970 to 1986. (b) Estimated number of juvenile coho salmon (bars) in Carnation Creek and the number of brood-year females (line). Data from Hartman and Scrivener (1990)

well understood, but may have included the effect of distance from spawning sites to downstream traps.

Mack Creek, a small (3.2-m average width) headwater tributary of the McKenzie River in western Oregon, contains a population of resident cutthroat trout that has been studied since the early 1970s as part of long-term ecological investigations in the H.J. Andrews Experimental Forest. A portion

of the Mack Creek watershed was logged in 1965, and reference sites have been established in the clearcut and old-growth forested reaches of the stream. The trout population in the old-growth reach of Mack Creek has been less variable than trout populations in the AWS sites, but in all but one year in which both old-growth and clearcut reaches have been sampled, densities were greater in the reach in which the riparian zone had been clearcut (Fig. 15.6). This trend was consistent with other comparisons of salmonids in clearcut and old-growth streams of the Cascade Mountains (Murphy and Hall 1981; Hawkins et al. 1983; Bisson and Sedell 1984; Bilby and Bisson 1987) and differs from the results of the AWS, in which a significant decrease in trout populations was found after logging. The high-gradient Cascade streams in Oregon showed minimal increases in sediment and temperature after clearcutting. This contrast, along with increased food production and higher foraging efficiency of trout in the clearcut Cascade streams, compared with those in old-growth (Wilzbach et al. 1986), may have contributed to the different response.

Studies of Supplementation

Nickelson et al. (1986 and unpublished) examined the effects of supplementing naturally spawned coho salmon populations in Oregon coastal streams with hatchery-produced fry. They measured summer populations in 15 stocked and 15 unstocked control sites from 1980 to 1985, and in four unstocked sites from 1988 to 1993. In the 1980-1985 period both juveniles and brood-year adults were censused, while in the 1988-1993 period juveniles and smolts were censused. Only trends from the 15 naturally spawned (unstocked) populations are reported here, as these are most relevant to the AWS. From 1980 to 1984, summer densities of coho salmon tended to decline in the unstocked control sites, followed by an increase at all sites in 1985 (Fig. 15.7). During this period, fish populations in the AWS sites were not monitored; thus, we were not able to determine if a trend similar to that observed by Nickelson et al. (1986) occurred at the Alsea small watersheds over the same interval. Two larger streams in the Alsea River basin (Horse Creek and Drift Creek) were included in the Nickelson et al. (1986) study, and presumably reflected trends in the Alsea small watersheds. Summer coho salmon densities in Carnation Creek also exhibited erratic declines from 1980 to 1986 (Fig. 15.5). The early 1980s, therefore, appeared to be a period of overall declining abundance of coho salmon in the region.

In the Oregon coastal streams there was a general correspondence between numbers of brood-year adults observed in spawning surveys and corresponding juvenile densities the following summer (Fig. 15.7b), suggesting, as in the AWS, that numbers of juvenile coho salmon rearing in the streams studied by Nickelson et al. (1986) were somewhat influenced by adult escapement. Returns of naturally spawning adult coho salmon to the Oregon coast over the past two decades have been reported to be below levels needed to adequately colonize

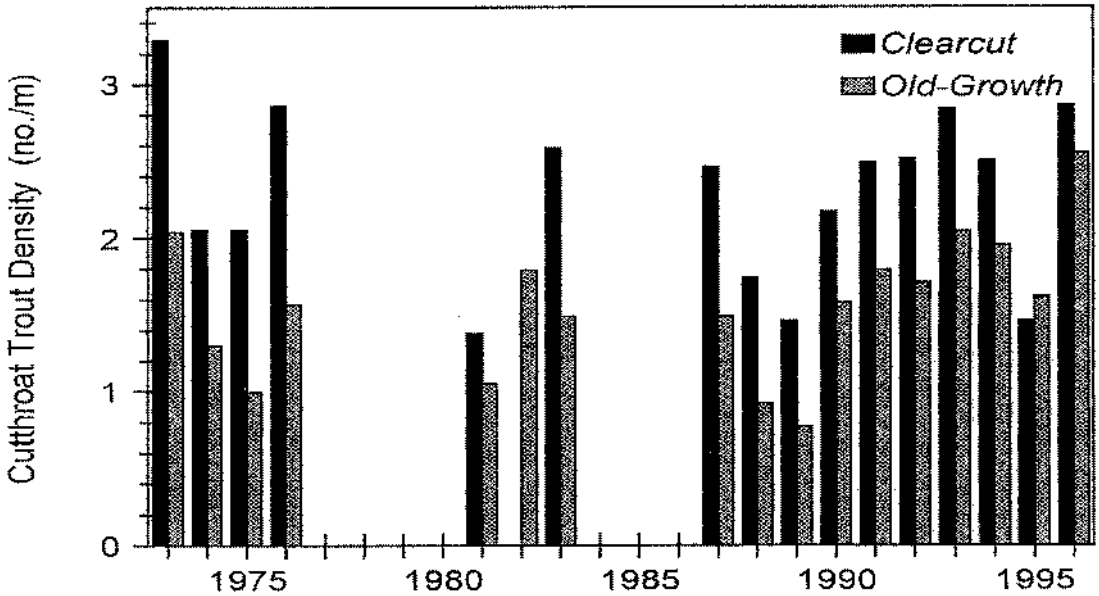

Fig. 15.6 Cutthroat trout densities in old-growth, forested, and clearcut sections of Mack Creek, Oregon, a stream with an average summer wetted width of 3.2 m (Moore and Gregory 1988). Data from several studies summarized by S. Gregory, R. Wildman, and L. Ashkenas (unpublished)

available habitats in coastal river systems (Nickelson et al. 1992). The positive association between number of spawners and juvenile densities supports the hypothesis that during the early 1980s low numbers of returning adults produced too few offspring to fully use available rearing space.

Studies of Habitat Enhancement

The Fish Creek watershed in the Mt. Hood National Forest of Oregon has been the site of a large-scale attempt to rehabilitate stream habitat throughout a 5th-order drainage system with approximately 16.7 km of habitat used by anadromous salmonids (Reeves et al. 1990). Fish Creek is a tributary of the Clackamas River, a subbasin of the Willamette River, draining the northwestern foothills of Mt. Hood in the Cascade Range of Oregon. The biophysical features of the stream differ in some important respects from those of the AWS sites. The predominant rock type in Fish Creek is volcanic, stream channels tend to be relatively steep with abundant coarse and little fine sediment, and much of the watershed is within the transient winter snow zone. Winter steelhead and, occasionally, fall Chinook salmon spawn in Fish Creek. Both species are essentially absent from the AWS sites, although they do occur in larger streams within the Alsea basin. Fish Creek also supports coho salmon and cutthroat trout, but both species tend to be far outnumbered by juvenile steelhead.

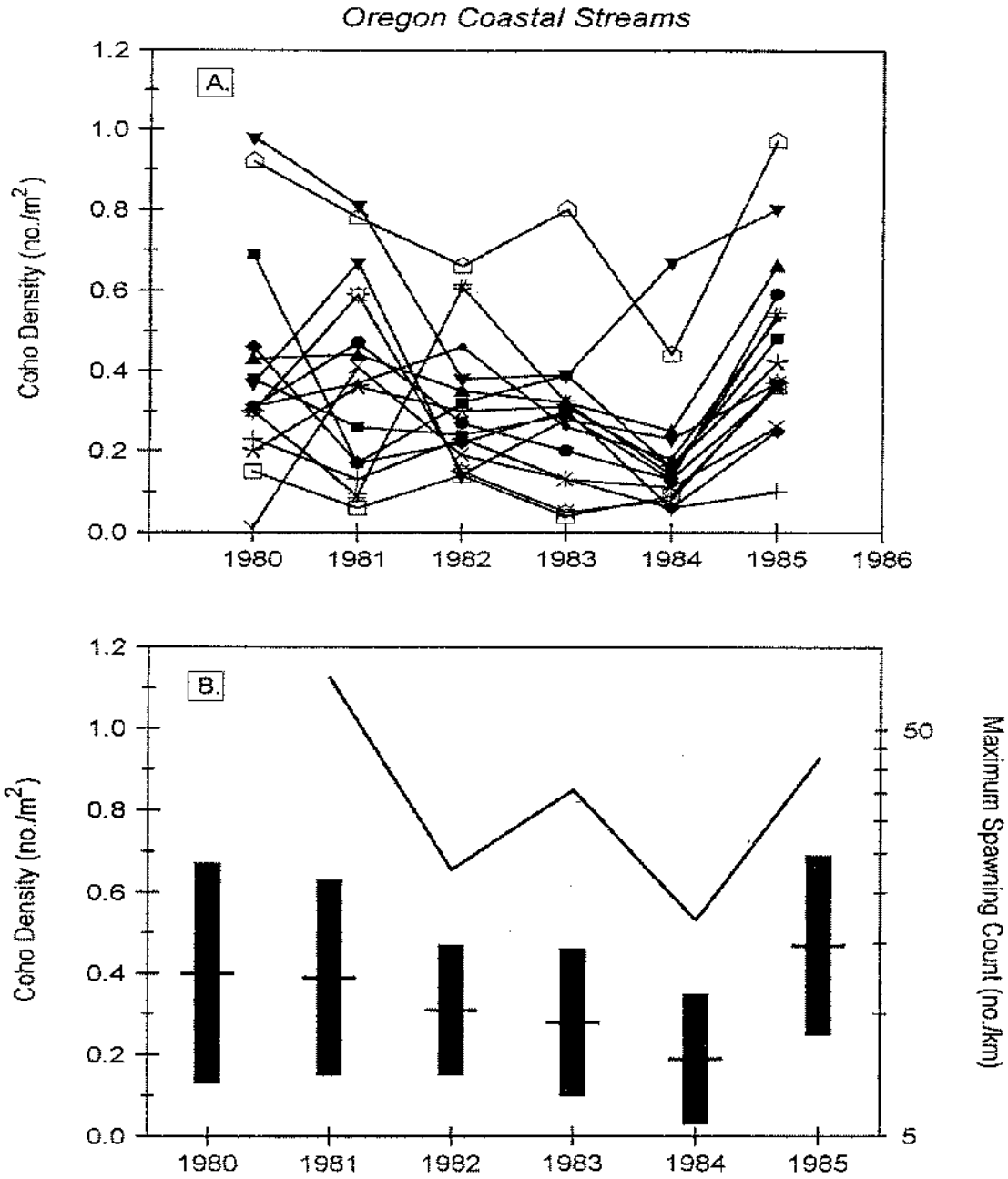

Fig. 15.7 (a) Density of juvenile coho salmon in 15 unstocked coastal Oregon streams from 1980 to 1985. (b) Densities of juvenile coho salmon (mean ± 1 SD) and mean peak number of adults (line) for the same streams. Data from Nickelson et al. (1986) and T. Nickelson (unpublished)

Beginning in 1983 and continuing until 1988, over 1,400 structures were placed in the mainstem and selected tributaries of Fish Creek. Most of these structures were combinations of logs and boulders that were placed to create pool habitat, store coarse sediment, improve cover, and increase hydraulic complexity. Off-channel ponds were created in lower Fish Creek in the early

1980s to increase winter rearing habitat, and road crossings known to block fish migrations were repaired to allow both adult and juvenile salmonid passage.

Estimated total numbers of juvenile anadromous salmonids in Fish Creek during summer were highest in the middle 1980s but dropped steadily during the latter part of the decade despite the extensive effort to improve habitat conditions (Fig. 15.8). Total declines were made up in large part by reduced numbers of age-0 steelhead. Age-1 steelhead and age-0 coho salmon were about as abundant in the late 1980s as in the early part of the decade. Pool habitat in Fish Creek doubled as a result of enhancement activities (Reeves et al. 1990). It is possible that the reduction in age-0 steelhead, which tend to prefer riffles (Bisson et al. 1988), may have been related in part to conversion of riffle habitat to pools. There was no apparent association between summer juvenile density and the strength of brood-year adult escapement to Fish Creek for either steelhead or coho salmon (Fig. 15.9) during the 1980s. There did appear to be a weak inverse relationship between the numbers of salmon and steelhead smolts from 1985 to 1990 (Fig. 15.10), hinting at the possibility of interspecific competition. Such a relationship did not occur in the Alsea Watershed streams because steelhead did not inhabit these small drainages.

Habitat enhancement was done in the Keogh River of northern Vancouver Island, British Columbia, in 1977 (Ward and Slaney 1979). The Keogh River is much larger than any of the AWS sites, with a watershed area of 129 km^2 and a mean annual discharge of 9.24 $m^3 s^{-1}$. Like Fish Creek, the salmonid community is dominated by juvenile steelhead. Most of the structures placed in the

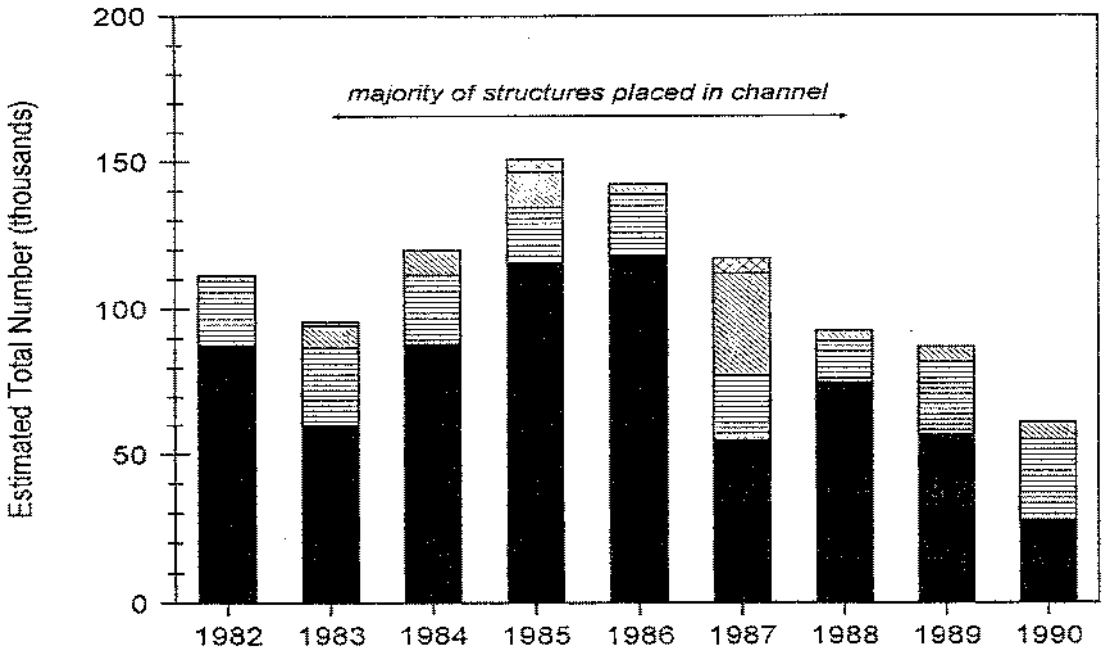

Fig. 15.8 Estimated numbers of juvenile steelhead, coho salmon, and chinook salmon rearing in Fish Creek, Oregon, from 1982 to 1990. Data from Reeves et al. (1990)

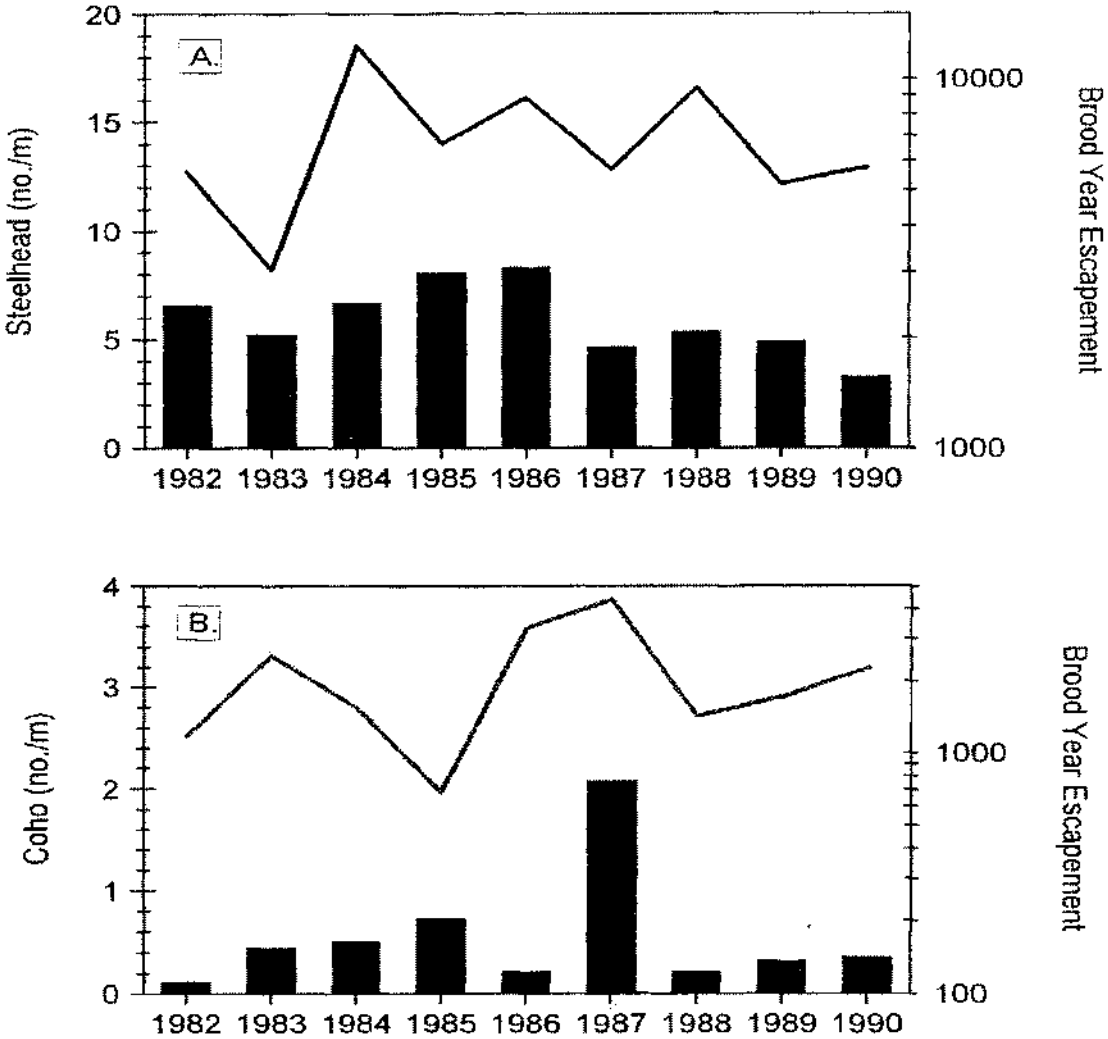

Fig. 15.9 Density of (a) juvenile steelhead and (b) coho salmon in Fish Creek (bars) and the number of brood-year adults (lines) passing a dam on the North Fork of the Clackamas River downstream from the mouth of Fish Creek. Data from Reeves et al. (1990)

channel of the Keogh River were boulder clusters or combinations of boulders and cabled logs, some of which broke loose quickly after initial placement. In addition, nutrients were continuously released in the upper Keogh River during summer in 1981 (Perrin et al. 1987). Annual surveys of the abundance of juvenile salmonids in the stream have shown that most boulder structures remained intact after 12-15 years. There was a net increase in carrying capacity for steelhead of about one fish per boulder (approximately 0.8 age-1 steelhead m^{-2}), and an increase in carrying capacity for juvenile coho salmon to about 0.3 fry M^{-2} in those sites where scour around the boulder clusters improved pool habitat (Ward and Slaney 1993).

Although the summer rearing density of juvenile salmonids in the Keogh River was much lower than at the Alsea study sites (Fig. 15.2), the positive response of both steelhead and coho salmon to habitat enhancement is

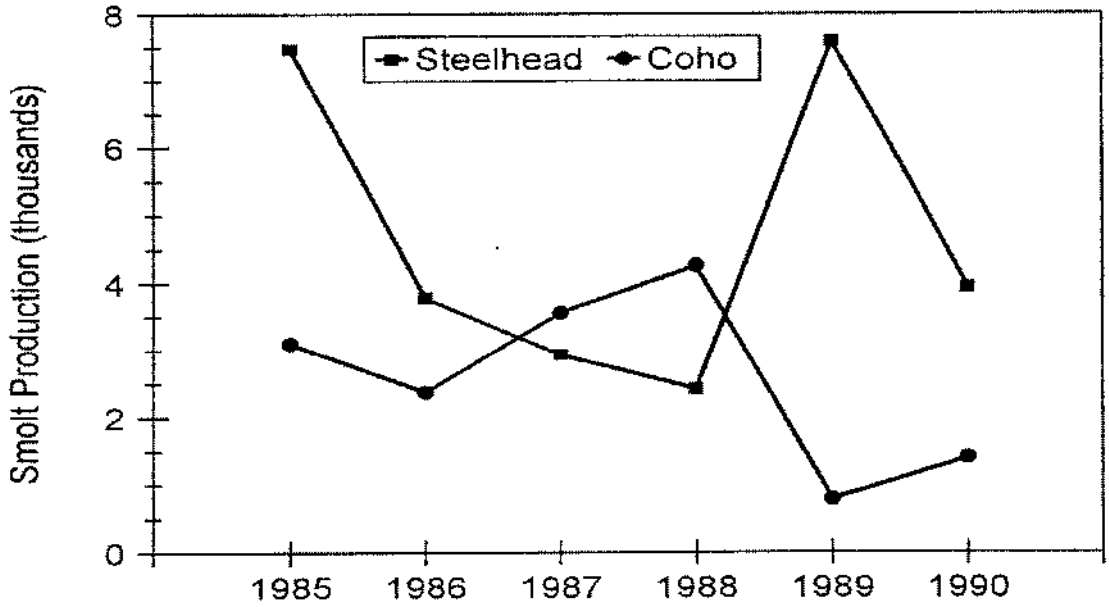

Fig. 15.10 Total production of steelhead and coho salmon smolts in Fish Creek from 1985 to 1990. Data from Reeves et al. (1990)

consistent with the hypothesis that habitat quality can influence the capacity of streams to support juvenile salmonids even when rearing densities are low. In spite of the relatively low salmonid densities reported for the Keogh River, the stream may have been at or near its carrying capacity. There was no obvious association between steelhead fry abundance and the abundance of brood-year spawners (Fig. 15.11a). It appeared that in the 1970s and 1980s sufficient numbers of adults were returning to the stream for their progeny to fully populate available rearing habitat, and that other factors (e.g., winter storms or other severe environmental disturbances) were controlling juvenile abundance. From 1977 to 1982, the period immediately after physical enhancement, increases were recorded in both steelhead fry and smolts produced per female relative to 1976, the year prior to structure placement (Fig. 15.11b). Ward and Slaney (1993) reported that these increases continued into the early 1990s, with the greatest increases accompanying stream fertilization (40-50% increase in numbers of salmon smolts, 62% increase in numbers of steelhead smolts, 40% increase in end-of-summer salmon fry weights). Thus, the Keogh River study provided early evidence that habitat enhancement and nutrient enrichment can successfully improve salmonid carrying capacity in an oligotrophic stream.

During the middle and late 1990s, however, anadromous salmonid populations in the Keogh River declined sharply to very low levels (Ward and McCubbing 1998). By 1998, adult steelhead returns numbered only 30 naturally spawned fish (33 additional adults were hatchery strays) and wild steelhead smolt production was less than 1,000 fish. The production of coho salmon smolts in 1998 was one-third of the 20-year average, and anadromous Dolly Varden *(Salvelinus malma)* populations were likewise in dramatic decline. Ward and

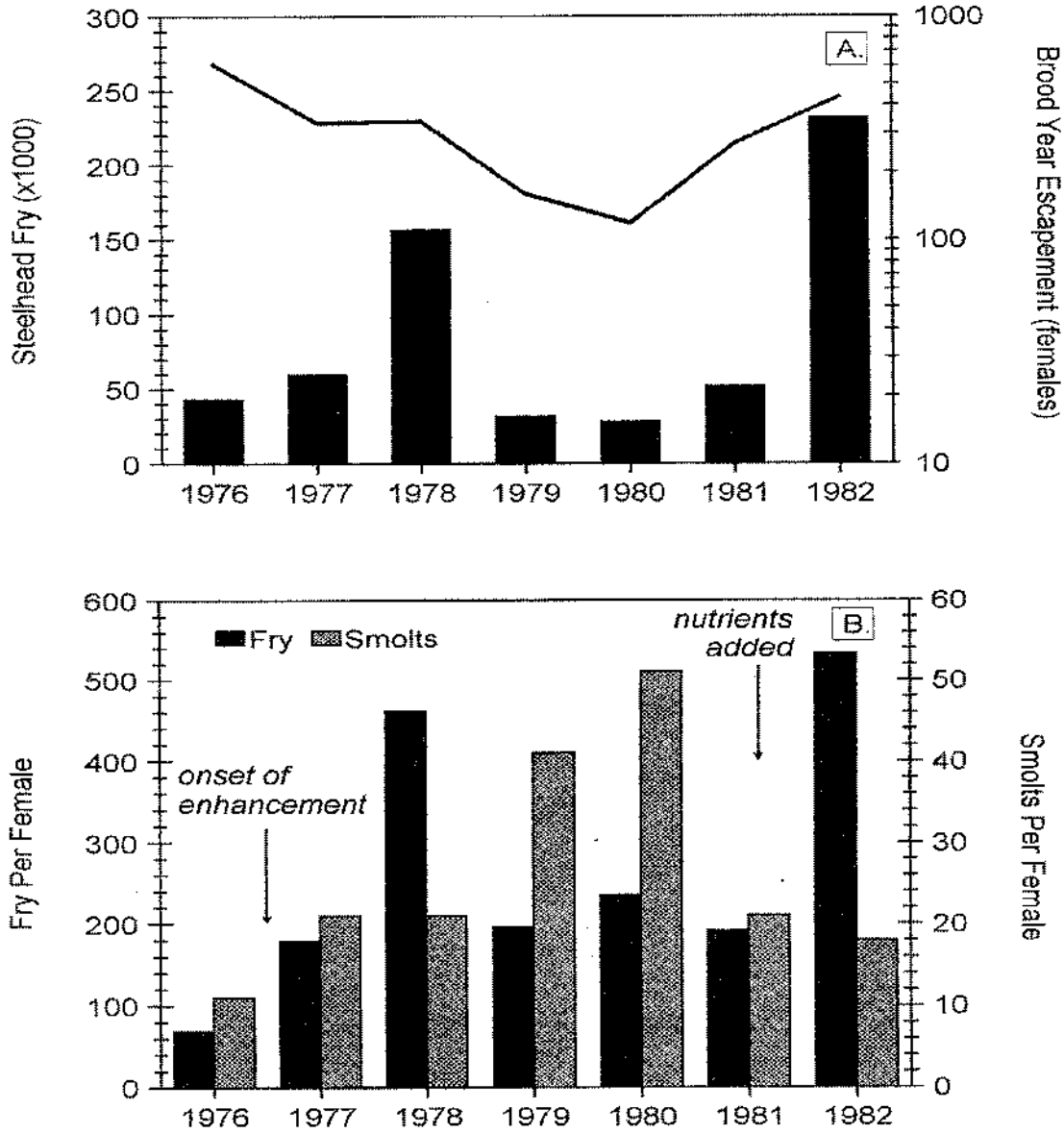

Fig. 15.11 (a) Estimated number of steelhead fry (bars) and escapement of brood-year female steelhead (line) to the Keogh River, British Columbia, from 1976 to 1982. (b) Number of fry and smolts produced per female steelhead. Data from Ward and Slaney (1993)

McCubbing (1998) believed that declines were related to low flows during spring, low numbers of spawning adults, and reductions in recruits per spawner. These trends suggest that the long-term benefits of habitat restoration can be overridden by other factors during the life cycle.

Other Multi-year Studies

In at least one other study the abundance of juvenile coho salmon appeared to be influenced by adult escapement, independent of habitat conditions.

Densities of coho salmon in lower Huckleberry Creek, a small tributary of the Deschutes River in southern Puget Sound, fluctuated sharply from 1986 to 1992 (B.R. Fransen and P. A. Bisson, unpublished) and tended to track the number of brood-year adults returning to the stream (Fig. 15.12). The Huckleberry Creek watershed is forested with second-growth Douglas-fir. The study site was not significantly altered during this period, although a debris torrent did occur above the study reach in January 1990, which increased suspended sediment and may have discouraged adult salmon from entering the stream that year.

Johnson Creek, like Mack Creek, is a small headwater tributary of Oregon's McKenzie River and was affected by a large debris torrent in 1986. The debris torrent originated in a first-order channel and swept through the entire length of Johnson Creek before coming to rest near the stream mouth. Summer trout population surveys began in 1988 and continued until 1992. A few cutthroat trout survived the debris torrent and non-anadromous rainbow trout have recolonized the lower reaches of Johnson Creek up to an impassable falls. In 1988, 2 years after the debris torrent, cutthroat trout density in the stream was approximately twice the average density observed in any of the Alsea study sites (Fig. 15.13), with most of the fish being underyearlings. In subsequent years the density of underyearlings declined sharply, and in 1992 the total cutthroat trout population in Johnson Creek had declined to a density less than half the average in the Alsea streams. The cause of the decline in Johnson Creek is not known,

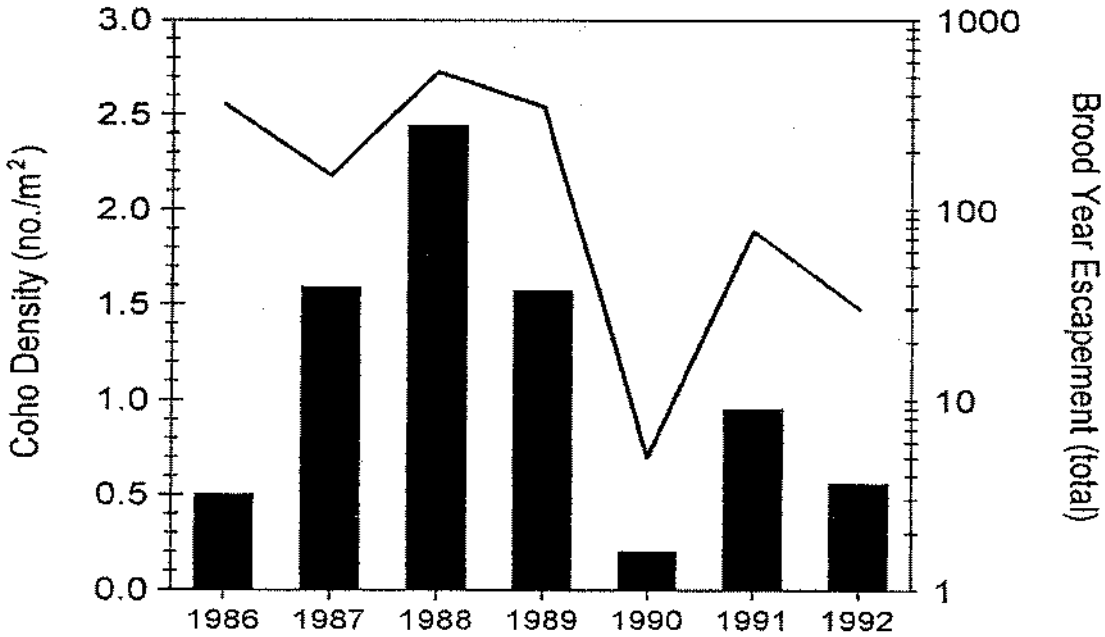

Fig. 15.12 Density of juvenile coho salmon (bars) and brood-year adult escapement (line) in lower Huckleberry Creek, Washington from 1986 to 1992. Data from B. Fransen and P. Bisson (unpublished) and Washington Department of Fish and Wildlife (unpublished)

but may have been related to unstable spawning substrate and to a reduction in food availability related to establishment of dense stands of young red alder *(Alnus rubra)* that heavily shaded the stream, as well as a dramatic proliferation of the snail *Juga plicifera* that could have sequestered much of the stream's primary production.

Interannual Variation

The interannual variability of adults, juveniles, and smolts in most of the multi-year studies (Table 15.3) was relatively high; the coefficient of variation was often 50% or greater. High levels of interannual variation in salmonid abundance have also been noted by other investigators (Lichatowich and Cramer 1979; Hall and Knight 1981; Grossman et al. 1990). Using two-way ANOVA, we detected no significant differences in variability among species or age groups of anadromous salmonids, i.e., no species or age groups appeared to be inherently more variable than others, although there were far fewer long-term studies of steelhead or cutthroat trout than of coho salmon in the Pacific Northwest. The interannual variability of adult coho salmon was significantly greater than the interannual variability of either juveniles or smolts (Table 15.4; $p = 0.02$, one-way ANOVA), but adult steelhead were not significantly more variable from year to year than juveniles or smolts.

It was difficult to determine from available data if anthropogenic disturbance resulted in increased interannual variation in juvenile salmonid populations, a major conclusion of the Carnation Creek study (Hartman and

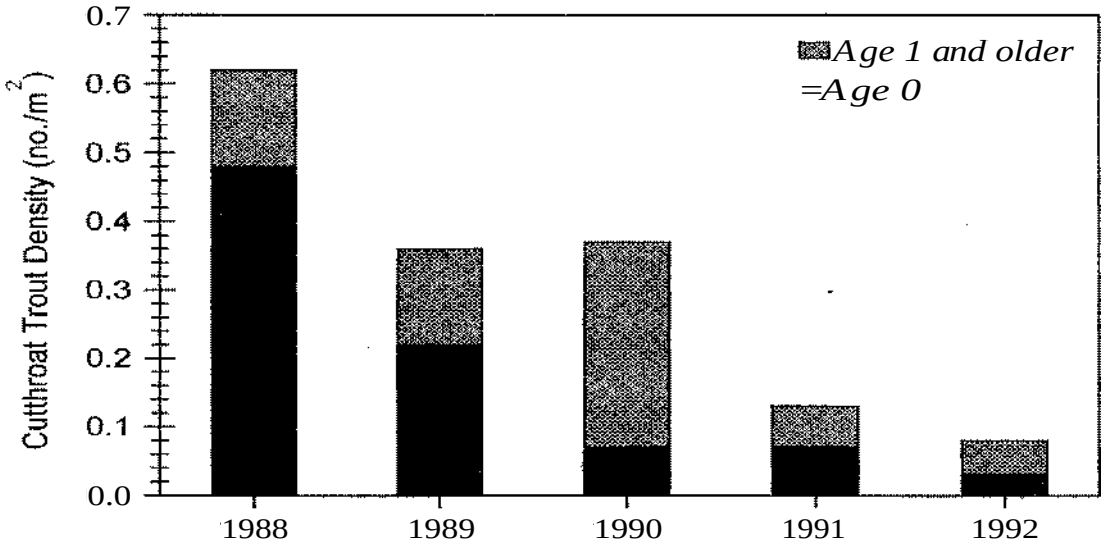

Fig. 15.13 Density of age-0 and age-1 and older cutthroat trout in Johnson Creek, Oregon. Data from P. Bisson and B. Fransen (unpublished)

Table 15.3 Coefficient of variation of the interannual abundance of salmonids in multi-year Pacific Northwest stream studies. Sources of data are given in Table 15.1

	Coefficient of variation (%)								
	Coho salmon			Steelhead			Cutthroat trout		
Streams and years	Adult	Juvenile	Smolt	Adult	Juvenile	Smolt	Adult	Juvenile	Smolt
Alsea Watershed Study (1959-74)									
Flynn Creek	96	55	58					23	
Deer Creek	55	33	35					22	
Needle Branch	79	71	50					64	
(1988-96)									
Flynn Creek		36						32	
Deer Creek		52						36	
Needle Branch		74						126	
Oregon coastal streams (1980-85)									
Panther Creek	39	37							
Rogers Creek	42	47							
Misery Creek	67	34							
Doe Creek	117	86							
Dogwood Creek	85	74							
Billie Creek	80	54							
N. Fk. Beaver Creek	42	34							
Horse Creek	47	25							
Drift Creek	61	52							
Hayes Creek	88	36							
Salmon Creek	85	53							
Deer Creek	69	81							
Neskowin Creek	49	64							
Louie-Baxter Creek	127	32							
Bear Creek	85	54							

Table 15.3 (continued)

	Coefficient of variation (%)								
	Coho salmon			Steelhead			Cutthroat trout		
Streams and years	Adult	Juvenile	Smolt	Adult	Juvenile	Smolt	Adult	Juvenile	Smolt
Oregon coastal streams (1988-93)									
East Fk. Lobster Creek		35	26						
Upper Lobster Creek		45	59						
East Fork Creek		51	48						
Moon Creek		66	82						
Clackamas River									
Fish Creek (1983-90)	54	109	53	40	28	48			
McKenzie River									
Mack Creek (1973-96)									
Clearcut								25	
Old-growth								30	
Johnson Creek (1987-92)								69	
Coos River									
Lost Creek (1986-93)					62				
Olympic Peninsula streams (1981-86)									
Siebert Creek			75		78	26			73
McDonald Creek			28		59	60			64
Deschutes River									
Huckleberry Creek (1986-92)	93	70							
Vancouver Island									
Carnation Creek (1970-87)	54	42	31	88	76	91	92	112	55
Keogh River (1976-82)				52	91	23			

Table 15.4 Average coefficient of variation of the interannual abundance of salmonid adults, juveniles, and smolts based on the data of Table 15.3. An asterisk denotes a significant difference ($p \leq 0.05$, single classification ANOVA) in comparison with other life stages of that species. The number of populations is shown in parentheses

	Coefficient of variation (%)		
Species	Adult	Juvenile	Smolt
Coho salmon	72* (21)	54 (28)	50 (11)
Steelhead	60 (3)	66 (6)	50 (5)
Cutthroat trout	92 (1)	54 (10)	64 (3)

Scrivener 1990). Except for the AWS, most experimental designs and objectives precluded such a determination; however, the interannual variability of both juvenile coho salmon and cutthroat trout in Needle Branch (the clearcut watershed) exceeded juvenile variability in both the patchcut and control watersheds (Table 15.3), a finding consistent with the Carnation Creek results. Moreover, variability of juvenile cutthroat trout in the clearcut stream was substantially greater during both post-logging periods than during prelogging for all measures of abundance (no. m^{-1}, no. m^{-2}, and g m^{-2}). There was no consistent trend in the other two watersheds. Variability of juvenile coho salmon in the clearcut stream also showed the same pattern of increase in both post-logging periods, however variability sometimes also increased in the other two streams (See Chapter 14). Additionally, the interannual variation of resident cutthroat trout in Johnson Creek, the stream altered by a large debris torrent, was over two-fold greater than in the old-growth forested section of nearby Mack Creek, which did not experience a major disturbance over the monitoring period.

The high level of interannual variability among salmonid populations in Pacific Northwest streams poses serious challenges for research seeking to detect significant responses to either environmental degradation or habitat improvement (Lichatowich and Cramer 1979; Hall and Knight 1981). Based on a fairly conservative estimate of interannual CV of 50% for anadromous salmonids (Table 15.4), it is possible to determine how many years of monitoring would be required to be 80% certain of detecting a given difference in population abundance between pre- and posttreatment means at a significance level of $p \leq 0.10$ (Sokal and Rohlf 1981). For treatments resulting in a 50% change in populations, a monitoring period of 26 years (13 years pretreatment and 13 years posttreatment) would be required. For treatments resulting in a 30% change in populations, a monitoring period of 70 years would be required, clearly an unrealistic requirement. Though improvements have since been made in experimental designs (Walters et al. 1988; Underwood 1994), it appears that long-term monitoring can, at best, detect only large changes in salmonid population abundance, and it is therefore not surprising that the two most

definitive multi-year fishery investigations in the region, the AWS and the Carnation Creek study, have spanned about two decades. We agree with Lichatowich and Cramer (1979) that 20 years should be considered the minimum time necessary to evaluate the influence of land-use practices or stream habitat restoration on salmonid populations in experimentally treated watersheds and that even longer studies will be necessary to significantly improve our ability to detect true differences.

Conclusions

The AWS remains one of the most comprehensive long-term fishery investigations in the Pacific Northwest. The research has been successful in part because scientists participating in the study realized the value of multi-year investigations in an environment prone to considerable interannual variability. Subsequent investigations in other streams have generally supported key findings of the Alsea fishery studies: (1) salmonid populations change as a result of anthropogenic disturbance, often in unpredictable ways, and (2) population abundance can become more variable after stream habitat is altered. The issue of increased variability with anthropogenic disturbance will become ever more important as we assess -population viability for salmonids at risk of extinction. Both trends in abundance and. interannual variability play important roles in population viability; relatively slight downward trends (as might be caused by long-term climate cycles), combined with increasing variability, significantly increase the risk of population extirpation (Lawson 1993).

In terms of actual standing stocks, salmonids in the Alsea tributary watersheds were often more abundant on an areal basis than populations in other streams, particularly those in northern Washington and on Vancouver Island, British Columbia. It seems possible that regional differences in biological productivity are mediated by differences in biogeoclimatic regimes, especially temperature and nutrient levels. The dramatic increase in juvenile salmonid productivity after nutrient enrichment of the Keogh River suggests that northern streams are food limited, a condition that may be somewhat less significant in western Oregon where temperatures and nutrient levels are generally higher.

Another factor that influenced anadromous salmonid abundance at some sites was the escapement of adults. Juvenile coho salmon in particular were often affected by the number of returning spawners, suggesting that population levels were recruitment limited. Most of the multi-year investigations took place after 1976, during a period of widespread decline of coho salmon populations in Washington and Oregon (Nickelson et al. 1992; Washington Department of Fisheries et al. 1993). Low escapements of naturally spawning

adults and the subsequent inability of progeny to fully populate available rearing space hindered assessment of the effects of habitat alteration on anadromous salmonids in some studies. Until numbers of adults sufficient for adequate habitat colonization are permitted to return to natal streams, our ability to detect the effects of habitat degradation or to evaluate the effectiveness of restoration programs will be severely limited. Indeed, the presence of abundant adult carcasses may itself be an important factor controlling the production of subsequent offspring (Bilby et al. 1996).

Production of juveniles migrating from experimentally controlled watersheds, expressed as numbers of migrants per adult female, proved to be a useful measure of the effects of logging on salmon populations in both the Alsea Watershed and Carnation Creek studies. These two parameters, adult escapement and numbers of downstream migrants, are often neglected in multi-year investigations because of the necessity of two-way fish traps and the time and expense of daily trap cleaning and checking. However, these traps yielded valuable data that were relatively immune to variations in year-to-year abundance, and we recommend that two-way fish traps be incorporated into other multi-year studies where possible. Recently, the importance of movement to resident salmonid populations has been documented (Gowan et al. 1994) as an important means of dispersal for mobile population members. Because knowledge of movements is critical to understanding any long-term study of salmonid ecology (Fausch and Young 1995), two-way traps should be employed in all long-term Studies whether of anadromous or resident populations.

Finally, our comparison of multi-year studies revealed the value of continuous monitoring for periods of decades rather than years. Many of the studies lasting from 5 to 10 years did not produce reasonably clear answers to the questions they were designed to address. One of the most daunting problems has proved to be interannual variations in population abundance on the order of 50% or greater for all life history stages of coho salmon, steelhead, and cutthroat trout. This relatively high level of variability will require continuous monitoring for at least two decades, as well as creative experimental designs that partition variation due to yearly climatic and other differences (Walters et al. 1988, 1989), in order to detect even coarse-scale changes in population abundance. Over the course of their multi-decade histories, studies such as those at the Alsea Watershed and Carnation Creek have provided some of the most valuable information about salmonid ecology in the Pacific Northwest. Such studies should be continued, as there is no reason to believe that they have yet yielded all there is to be learned at these sites.

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