Culture of Atlantic Salmon, *Salmo salar*, in Puget Sound

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ABSTRACT—Atlantic salmon, Salmo salar, *stocks are extremely low in New England streams. A pilot study conducted in Puget Sound, Wash., showed that Atlantic salmon brood stock could be reared successfully by combining special techniques of fry rearing and saltwater pen culture as used for Pacific salmon. Fingerlings smolted at 13-15 months of age and first adult spawning occurred at 4 years of age. Smolt size varied in different groups from an average weight of 19.6-200 g (0.70-7.0 ounces). The 1971 and 1974 brood Atlantic salmon spawned for the first time at 4 years of age, when they were averaging about 4.0 kg (8.8 pounds) and 4.2 kg (9.4 pounds), respectively. Survival of the 1971 and 1974 broods in salt water from smolt to mature adult was 90.3 and 81.1 percent, respectively. The egg survival through hatching was 82.7 and 71.4 percent, respectively.*

Introduction

Depletion of the Atlantic salmon, *Salmo salar*, from lakes and streams in New England began in colonial times and increased as industrialization intensified (Netboy, 1968). Obstructing dams, siltation due to lumbering and sawmill activities, industrial pollution, and uncontrolled fishing led to the disappearance of salmon from most of the region.

Abatement of pollution and construction of fishways around dams were begun in attempts to return streams to habitable conditions and restore salmon runs to their earlier abundance. To restock the streams and reestablish the species' complete life cycle, a source of eggs is necessary. This could be provided by adult spawners (or a brood stock).

In 1971, National Marine Fisheries Service (NMFS) scientists in the agency's Northeast Regional Office proposed a feasibility study and pilot test in the Pacific Northwest (Puget Sound, Wash.) to rear Atlantic salmon from the egg to spawning stage to produce eggs for subsequent shipment to New England hatcheries. A total rearing system, using net-pen culture in salt water, would make it possible to establish sufficient brood stock from virtually any stock desired.

The advantages of raising these fish in the Pacific Northwest rather than New England are: 1) Sheltered waters of Puget Sound, 2) mild climate, and 3) surface water temperatures ranging from 6° to 16°C each year as opposed to much colder winter temperatures and warmer summer temperatures on the New England coast (Colton and Stoddard, 1972).

Saltwater culture systems appear to be a good technique for raising a brood stock of selected species. Saltwater systems for raising captive Atlantic salmon brood stock are successful in both Norway and Scotland[1,2].

Coho salmon, *Oncorhynchus kisutch*, have been reared in a pilot brood stock rearing study at the NMFS Northwest and Alaska Fisheries Center's Manchester Marine Experimental Station, Manchester, Wash., which specializes in aquaculture research. Using net pen rearing techniques similar to those used for commercial production of marketable pan-size Pacific salmon (*Oncorhynchus* spp.), broodstock coho salmon were successfully reared to maturity in their second or third year of age. Survival ranged from 5 to 85 percent of the eggs produced by individual females (Novotny, 1975).

The specific objectives of the Atlantic salmon pilot study were to: 1) Establish a successful methodology for rearing Atlantic salmon smolts; 2) determine growth rate and survival of smolts reared to maturity in saltwater net pens; 3) determine relative resistance of Atlantic salmon to disease organisms indigenous to Pacific Northwest waters; and 4) establish maturation schedules, fecundity, and fertility of adult female Atlantic salmon reared to maturity in saltwater net pens.

Atlantic salmon needed to initiate the study were obtained from the Wizard Falls Hatchery of the Oregon Department of Fish and Wildlife (ODFW) as parr (1971 brood) or eyed eggs (1972 and 1974 broods). The Wizard Falls Hatchery stocks are the progeny of parents that were 6-10 generations removed from anadromous salmon from the Gaspé Peninsula in Quebec, Canada, near the entrance to the St. Lawrence River. Although this was strictly a pilot test, the stock used was considered typical of the New England region.

Fish from the 1975 brood, used only

[1]Lecture at the University of Washington, Seattle, on "Atlantic Salmon in Norway" by Magnus Berg, 24 November 1972.

[2]Needham, E. A. The salmonid pathologist in 1977. *In* Proceedings from the International Symposium on Diseases of Cultured Salmonids, April 4-6, 1977, Seattle, Wash., p. 8-15. Tavolek, Inc., Seattle, Wash

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for fry-to-smolt growth and seawater adaptation information, were obtained from eggs of the first spawning of adults from the Manchester net pens.

Pilot Study Systems

For the Atlantic salmon brood stock program to succeed, it was necessary to establish successful techniques for handling the sequential changes from the egg stage through the spawning of the adult fish.

Incubation

Heath[3] incubators were used to incubate the eggs to hatching. Heath incubators and small shallow troughs with or without gravel substrate in the presence or absence of light were used for incubation of alevins to the swim-up or initial feeding stage. Incubation of the alevins in different environments produced fry of various sizes as indicated in Table 1. The two dark environments produced the heaviest fry which consequently elicited the superior feeding response in comparison with fry incubated in a lighted environment. Research on other salmonids has indicated that fry quality can be enhanced by incubating the alevins on gravel or artificial substrates[4] (Bams, 1973).

Freshwater Rearing

Fresh water, used for rearing the Atlantic salmon from fry to smolt stage, was maintained at saturation levels for oxygen. Ammonia nitrogen was held below 0.1 ppm by adjusting water volume, and pH was 6.8 to 7.2. Artificial fluorescent lighting was controlled to simulate a natural photoperiod regime.

Rearing tanks were cleaned daily. The Oregon Moist Pellet (OMP), standard diet for artificial rearing of Pacific salmon, *Oncorhynchus* spp., was used throughout the freshwater rearing.

Exacting culture techniques in the early rearing stages are critical for success in rearing Atlantic salmon.

[3]Reference to trade names or commercial products does not imply endorsement by the National Marine Fisheries Service, NOAA.

[4]Poon, D. C. 1977. Quality of salmon fry from gravel incubators. Auke Bay Lab., Northwest and Alaska Fish. Center, NMFS, NOAA, Auke Bay, Alaska. Unpubl. manuscr., 253 p.

Table 1.—Feeding response of Atlantic salmon fry incubated in four different conditions of light and substrate.

Brood year	Lot	Incubator type	Lighting	Substrate	Mean length (mm)	Mean weight (g)	Condition index $\frac{(w \times 10{,}000)}{L^3}$	Feeding response
1974	1	Heath	Indirect	None	27.3	0.146	0.72	poor
1975	2	Heath	Dark	None	29.7	0.211	0.81	good
1974	3	Trough (4' × 1')	Dark	Gravel	27.1	0.226	1.14	exc.
1974	4	Trough (4' × 1')	Indirect	None	[1]	0.180	—	poor

[1]Length data incomplete, not included.

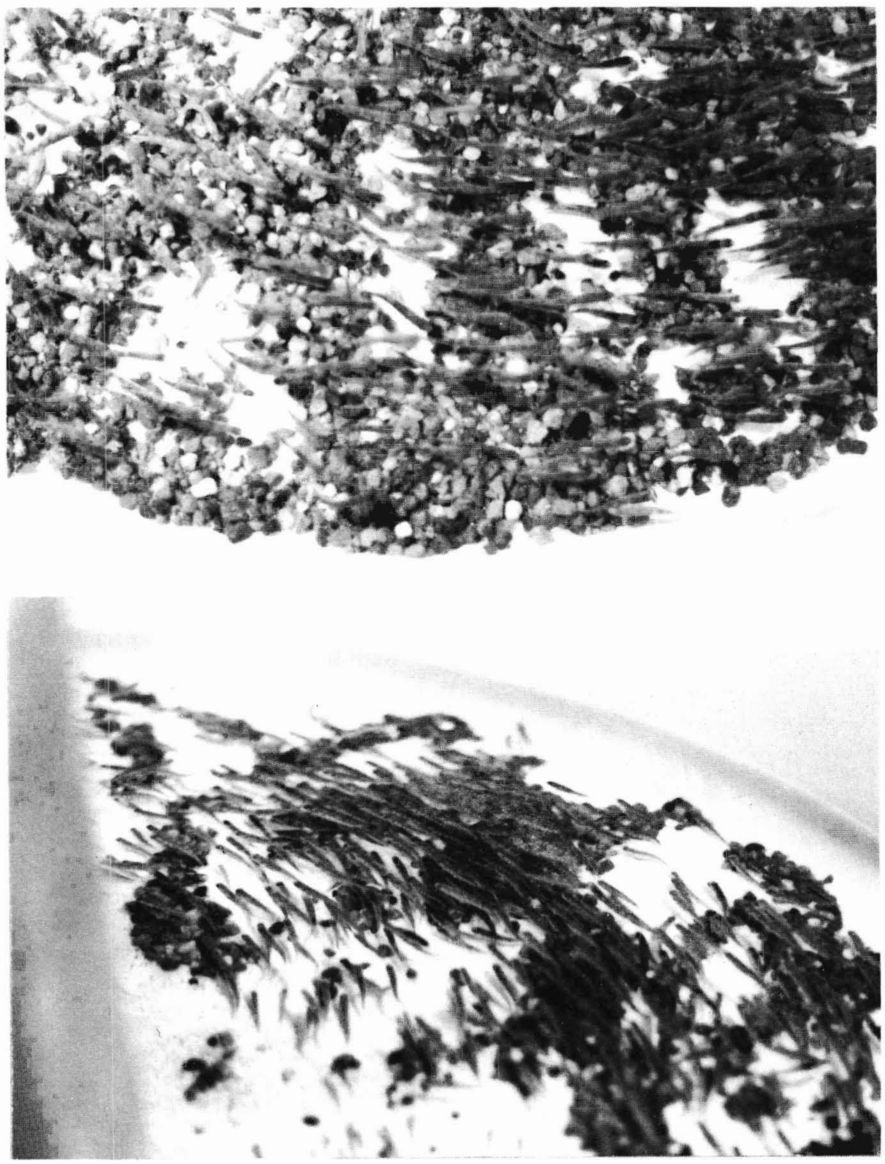

Figure 1.—Atlantic salmon fry in a circular tank with bottom substrate of pea-size gravel.

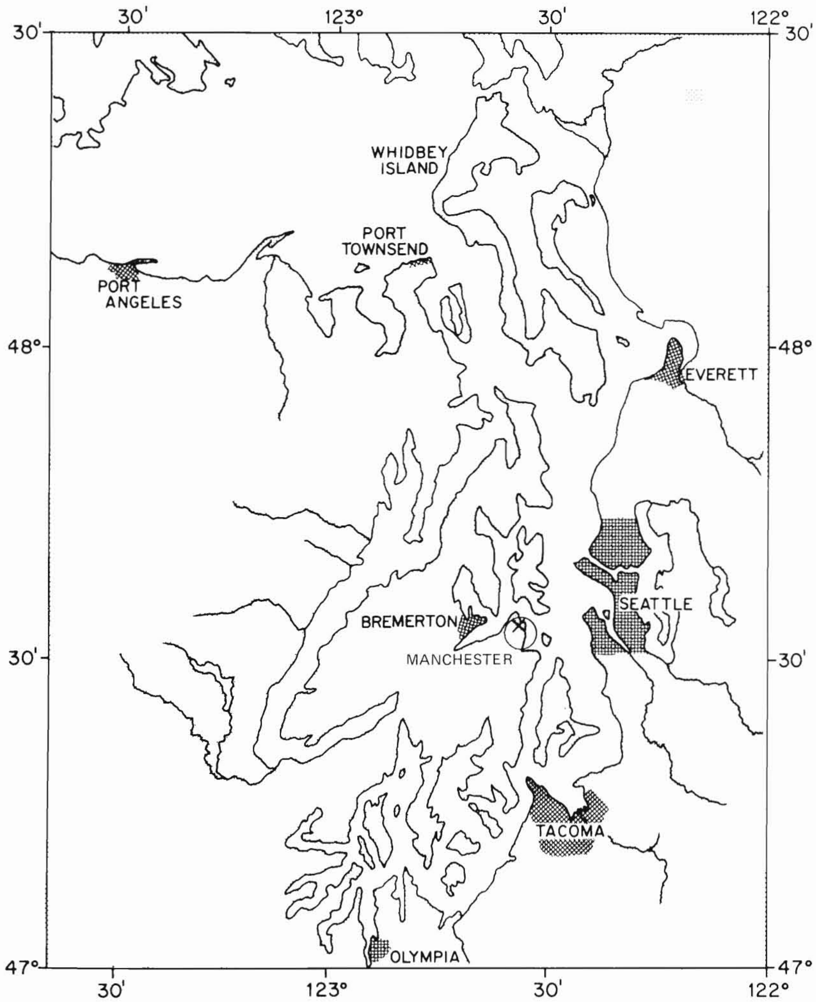

Figure 2.—Puget Sound, Wash., site of marine culture of Pacific salmon and pilot studies on Atlantic salmon at the NMFS Northwest and Alaska Fisheries Center, Manchester Marine Experimental Station (X), where aquaculture research is conducted.

After experimenting with many different rearing conditions, I found that the following conditions were most conducive to successful early rearing.

Circular Tanks

Circular tanks 1.2 m (4 feet) in diameter supplied with water moving at about 12-15 cm (0.4-0.5 feet) per second were nearly self cleaning and assured that the fish would continue to respond to artificial feeds (OMP). Even gravel-incubated fish responded poorly to artificial feeds when reared in straight troughs with water velocities from 3 to 15 cm (from 0.1 to 0.5 feet) per second.

Shallow Water

Newly emerged fry continued to respond well to artificial foods when kept at a depth of 5-10 cm (0.16-0.32 feet). At greater depths, the fry stayed on the bottom. When the fish reached a weight of 1 g (0.04 ounce), the water depth was increased to 30 cm (0.98 feet) with no adverse effects on feeding response.

Bottom Substrate

Simulation of natural stream bottom substrate was necessary to prevent crowding of fry near the outlet screen (Fig. 1). Substrates of gravel or dark gray painted blotches caused the fish to disperse evenly. Plastic materials have also been suggested to simulate a bottom substrate for Atlantic salmon fry (Leon, 1975).

Proper Loading Densities

A rearing density of 200 swim-up fry per 900 cm^2 (1 foot^2) of tank produced smolts with minimum loss. One-half that density (100 fish per 900 cm^2) was used once the fish reached a size of 7 g (0.25 ounce). Substantially higher or lower densities were detrimental to feeding response and at higher densities disease incidence was greater.

Water Temperatures of 12.4°-13.2°C

Temperatures elevated by 2°-5°C over ambient to about 12.4°-13.2°C were necessary to evoke a surface feeding response from newly emerged fry. This procedure was essential to successful rearing with the OMP diet. At lower temperature the fish remained on the bottom, and excessive food accumulated on the bottom resulting in increased disease.

Saltwater Rearing

Saltwater rearing from smolt to adult stage was done at the Manchester Marine Experimental Station (Fig. 2). There, waters are protected by the mainland on the south and Bainbridge Island on the north. Salinity ranged from 26 to 30‰, and biweekly mean temperature varied from 7.1° to 13.9°C (range from 6.6° to 15.4°C) (Fig. 3) during the experimental rearing period.

The Atlantic salmon smolts were transferred directly from fresh water to salt water and held in floating, knotless, nylon net pens 1.2 × 2.4 m (4 × 8 feet) and 2 m (6.5 feet) deep. As the fish grew, the net pen size was increased to an eventual size of 4.8 m (16 feet) on a side with a maximum depth of 3.7 m (12 feet). Mesh opening (hanging) varied from 0.6 cm (0.25 inch) at the outset to 2.5 cm (1 inch) for adults. Commercial OMP diet was used throughout the saltwater rearing period with the exception of 10 percent supplemental feedings of crustaceans and whole anchovy or herring 2 months before spawning of the 1971 brood only. The fish were examined for growth and maturation on an intermittent basis (Fig. 4-7).

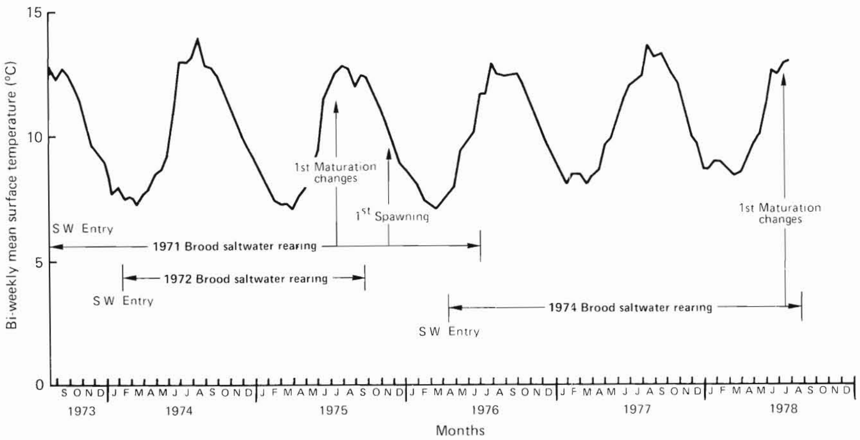

Figure 3.—Biweekly mean water temperatures during the saltwater rearing of 1971, 1972, 1974, and 1975 brood Atlantic salmon in Puget Sound, Wash.

Figure 4.—Net-pen reared Atlantic salmon, 2-5 kg (5.5-11.0 pounds), are crowded prior to removal for individual measuring

Results

Freshwater Growth and Survival

The optimum water temperature for growth of *Salmo* spp. is between 10° and 17°C (Huet, 1972). The winter temperatures of most natural fresh waters in North America decline to less than 7°C, whereas water temperatures during the summer may exceed 20°C. The result is that most Atlantic salmon from natural and artificial rearing environments of North America reach the smolting stage in their third spring (2+ years old). In many colder locations the smolt stage is not achieved until after 3+ years of rearing. Atlantic salmon must reach an approximate fork length of 10 cm (4 inches) near the end of the summer-fall growing season if they are to attain parr-smolt transformation in the spring (Elson, 1957); and for a variety of reasons, but primarily temperature, Atlantic salmon do not achieve the size at most rearing sites until the end of their second growing season.

However, Atlantic salmon smolts were produced in 13-15 months in Oregon when reared at a constant temperature of 10.5°C[5]. Likewise, in our growth trials we were able to produce yearling smolts using heated water ranging from 12.4° to 13.2°C (from 2° to 5°C over ambient) during fry rearing and temperatures ranging from 8° to 15°C for a substantial part of the remaining freshwater rearing period (Fig. 8). The smolts reared by NMFS from the 1972, 1974, and 1975 broods grew to mean weights of 22.6, 37.7, and 19.6 g (0.80, 1.33, and 0.70 ounces), respectively.

The much greater size achieved by the 1974 brood (Fig. 8) was at least in part due to their being reared in warmer water than the 1975 brood from the 18th to the 54th week after initial feedings. Total thermal units (T.U.) (1 T.U. = 1°C for 24 hours) accumulated were 4,600 and 4,100 for the 1974 and 1975 broods, respectively. The 1974 brood fry also emerged from gravel incubation at a greater average weight than the 1975 brood (Table 1). Growth of the 1972 brood was not plotted due to the lack of complete temperature data.

Survival of the experimental rearing lots in fresh water ranged from 0 to 86 percent. When the aforementioned rearing requirements were not met

[5]Morton, G 1972 Oregon Dep. Fish Wildl., Wizard Falls Hatchery, Sisters, Oreg Pers commun

in their entirety, survival was less than 40 percent in every case. However, when all conditions were met during the rearing of the 1974 and 1975 broods, the survival was 86 and 73 percent, respectively.

Seawater Adaptation

Yearling Atlantic salmon smolts from the 1972, 1974, and 1975 broods entered salt water in February, March, and April, respectively (Fig. 9) at weights ranging from 19.6 to 37.7 g (from 0.70 to 1.33 ounces). All were transferred directly from fresh to salt water when they exhibited visual signs of smolting, i.e., loss of parr marks, silvery appearance, decrease in the condition index value, and black fringe on caudal and dorsal fins.

Each of the stocks transferred survived at a rate of 96 percent or more for 30 days after transfer. Only the 1975 brood, which had a substantial number of fish under 10 cm (4 inches) in fork length, showed significant incidence of parr reversal or nonadaptation to salt water. Reversal was in approximately the same percentage (24 percent) as the number of fish under 10 cm (4 inches) in length.

The 1971 brood smolts were obtained from the ODFW as large parr in the summer of 1972 and were held in fresh water until they were 18 months old or about 5 months past the normal smolting age. At the time of saltwater entry they ranged in weight from 150 to 260 g (from 5.3 to 9.2 ounces). All fish (n = 31) over 180 g (6.3 ounces) in weight ($\bar{x}$ = 200 g or 7.0 ounces) survived the direct transfer to saltwater with no later

Figure 5.—A large adult Atlantic salmon is removed from the rearing pen for measurement.

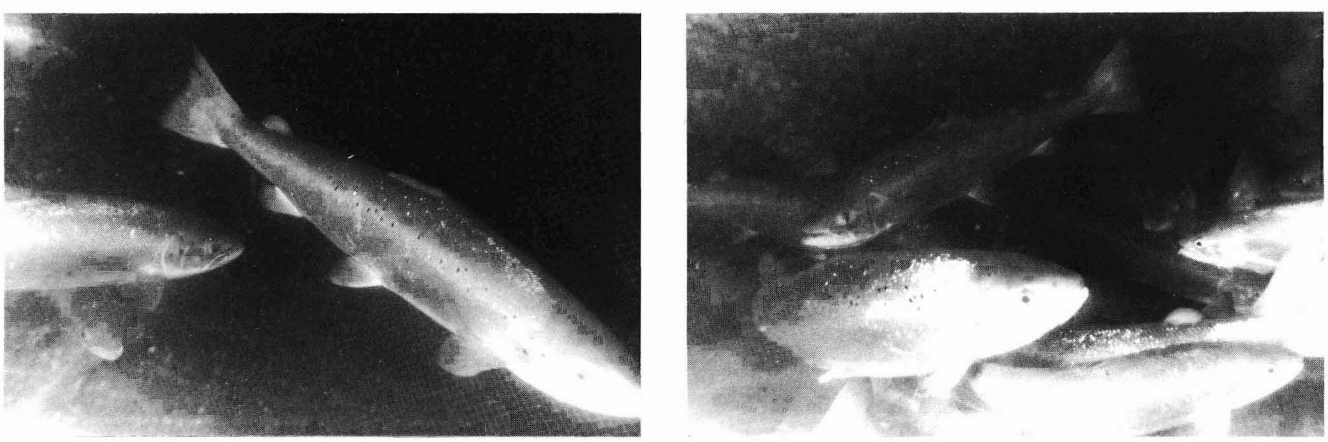

Figure 6.—Adult Atlantic salmon in net pens at Manchester, Wash.

reversion to parr. Only one of the smolts less than 180 g (6.3 ounces) survived in salt water for more than 2 months. Thus, successful saltwater adaptation in this stock of Atlantic salmon took place over the entire late winter-spring smolting period when the fish had reached a size of 10 cm (4 inches) or greater. But, when the fish were held beyond the normal smolting period, perhaps beyond the summer solstice (21 June), a much greater fish size was necessary to assure survival.

Saltwater Growth and Survival

Saltwater growth was plotted on a T.U. basis because of the widely varied saltwater entry dates for each of the smolt groups (Fig. 9). On that basis the 1972, 1974, and 1975 broods, which all entered salt water at the peak of smolting as determined by visual cues, grew to a similar size after 4,000 T.U. Thus, as expected, the smaller smolts grew faster, negating the apparent advantage of growing larger smolts. However, the smallest smolts (1975 brood) had a relatively high rate of parr reversals (24 percent). Parr were not included in growth analysis.

Growth of the 1971, 1972, and 1974 broods between 200 and 1,000 g (7.0 and 35.2 ounces) in weight was accomplished with a similar number of T.U.'s (2,600-3,000). However, their growth after that size was apparently affected by factors other than temperature. During that period the 1974 brood grew to 3.4 kg (7.5 pounds) using only about half the number of T.U.'s (2,600) used by the 1971 brood.

The slower growth of the 1971 brood was unexpected since they began that growth segment during early summer when the sea temperature was increasing. On the other hand, the rapid growth of the 1974 brood took place in the fall and winter months.

In July 1975, the growth of the 1971 brood declined, coinciding with the onset of maturation. By late February of 1976, maturing fish had recovered, and in the spring and early summer of 1976 a growth surge of about 2.0 kg (4.4 pounds) per fish occurred, resulting in a mean weight of 6.7 kg (14.8 pounds) and an upper range of 9.0 kg (19.8 pounds). This growth surge was coincidental with a rise in temperature from 7° to 12°C (Fig. 3).

The loss of all 1971 and 1972 brood Atlantic salmon to poachers shortly after the last weighing on 10 June 1976 prevented complete evaluation of growth, survival, and maturity through 5 years of total age.

Survival of the 1971 brood Atlantic salmon from the time of entry in salt water to the total age of 4 years was

Figure 7. —Individual Atlantic salmon are 1) anesthetized, 2) measured, and 3) returned to net pens

90.3 percent, while the 1974 brood survival after 24 months in salt water was 92.4 percent. Survival figures are not available for the 1972 and 1975 broods due to escape and animal predation. River otters, *Lutra canadensis*, were responsible for nearly complete losses of smolts—as many as 2,400 fish in a single night. Some of these smolts were eaten and others escaped through holes in the nets that had been torn by the otters.

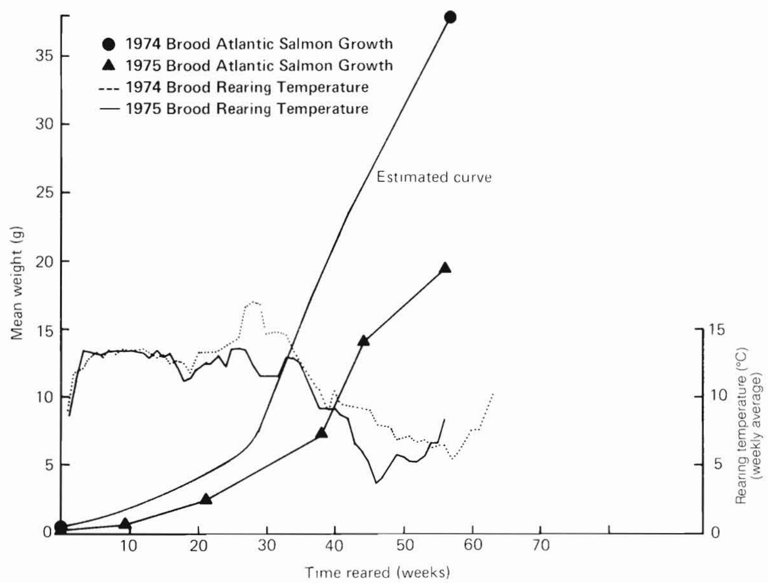

Figure 8.—Freshwater growth and rearing temperatures of Atlantic salmon reared at the Northwest and Alaska Fisheries Center, Seattle, Wash.

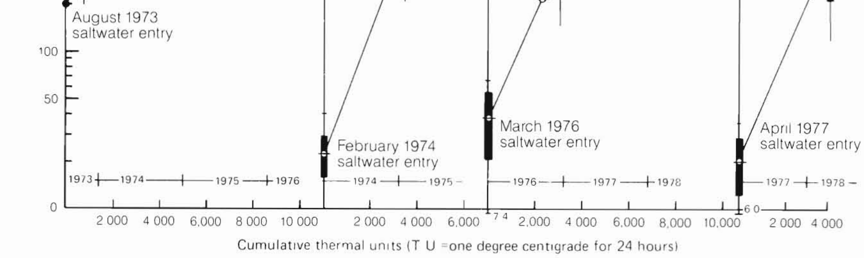

Figure 9.—Size range, mean, and standard deviation of Atlantic salmon reared in saltwater pens in Puget Sound, Wash.

Disease and Treatment

Resistance to endemic saltwater diseases of native Puget Sound fish was indicated by all of the Atlantic salmon groups reared at the Manchester site, with the exception of furunculosis, *Aeromonas salmonicida*. This disease was detected in the 1971 brood adults shortly before the first spawning 22 months after entry in salt water and in the 1975 brood smolts shortly after entry into salt water. The minor incidence of furunculosis in adult maturing fish was controlled by addition of the antibiotic chloramphenicol (Chloromycetin) at a level of 0.1 percent in the diet (Van Duijn, 1967). We have concluded that this treatment should be administered prophylactically at least 40 days prior to smolting and shortly before adult maturation.

Vibriosis, a saltwater bacterial disease common to Pacific salmon held in net pens in Puget Sound (Hodgins et al., 1977) and caused by *Vibrio anguillarum* was not a problem during our rearing of Atlantic salmon. To check for disease resistance, I purposely declined to vaccinate for vibriosis. The only detectable incidence of vibriosis occurred in the 1975 brood smolts shortly after entry in salt water and secondary to furunculosis. We observed that vibriosis is not a serious disease of the genus *Salmo*; cutthroat trout, *S. clarki*, and steelhead trout, *S. gairdneri*, both appear to have good natural immunity to the disease.

Minor occurrences of frayed fins and epidermal necrosis, typical symptoms of infections by myxobacterial organisms, were controlled with malachite green treatments at 1:19,000 concentration for 12 seconds and oxytetracycline (Terramycin) administered in the feed at the rate of 2 percent active ingredient for a period of 10 days.

Bacterial kidney disease (BKD), *Corynebacterium* sp., a previous problem with pen-reared brood stock of Pacific salmon[6], was not evident or

[6]Novotny, A. J. 1978. Manchester Marine Experimental Station, Northwest and Alaska Fisheries Center, NMFS, NOAA, Manchester, Wash. Pers. commun.

detected during routine etiological examinations of Atlantic salmon mortalities. Smolts of the 1971 brood were treated with the drug sulfasoxazole (Gantrisin) (10 g (0.35 ounces)/100 pounds of fish/day for 10 days) every 60 days prior to smolting as a prophylactic measure. None of the other broods were treated in any way to prevent BKD.

Sexual Maturation

Adults from the 1971, 1972, and 1974 broods matured in seawater. About 30-40 percent of the males matured at 3 years of age. However, no 3-year-old females matured. Both the 1971 and 1972 broods were progeny of 5-year-old parents (footnote 5), while the 1974 brood parents were 4 years of age.

Seven fish (4 males and 3 females) or 25 percent of the surviving 1971 brood fish (n = 28) matured at 4 years of age. We presumed that the remaining 75 percent would have matured in their fifth year with perhaps a few maturing in their sixth year. Two mature females were lost to osmoregulatory stress shortly before spawning, but a third female was successfully spawned with two males, producing 4,324 fertilized eggs. These eggs produced 3,580 hatched alevins (82.7 percent survival). The one female that was spawned had a fork length of 64.3 cm (25.3 inches) and a total weight of 3.4 kg (7.5 pounds). Postmortem examination of the other two mature females with fork lengths of 62.5 cm (24.6 inches) and 68.0 cm (26.8 inches) revealed 4,515 and 4,916 eggs, respectively.

Fifty females (72.5 percent of the 1974 brood adult females) matured at 4 years of age, indicating that age at maturity is influenced substantially by genetic factors. Forty-one of the females, averaging 4.1 kg (9.13 pounds) in weight, survived all aspects of handling. They produced an average of 5,625 eggs per female or 1,370/kg (616/pound) body weight and a total quantity of 230,650 eggs. The weight/fecundity relationship of the 1974 brood is shown in Figure 10.

The eggs of the three 1971 brood females appeared to be of excellent quality and were orange-red—possibly the result of the supplemental (10 percent of daily ration) feedings of fresh crustaceans and anchovy for 2 months prior to spawning. Eggs from the 1974 brood females, however, were pale yellow. No supplemental carotenoid was fed to the 1974 broodstock prior to maturation.

Of note is that the alevins produced from both the 1971 and 1974 brood adults did not develop pinched-off posterior portions of the yolk sac as noted by others working with this species (footnote 5) despite being incubated in a stock Heath incubator. All of the original lots we obtained from ODFW as eyed eggs produced alevins that had constricted yolk sacs during incubation, including those incubated in gravel. We have not yet determined the reason for this difference.

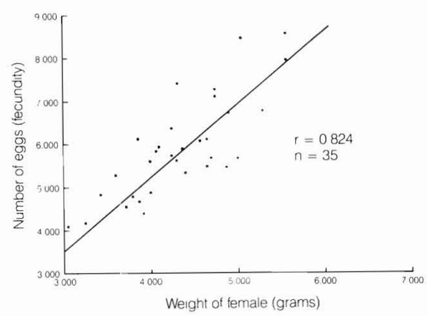

Figure 10.—Weight vs. fecundity relationship of 1974 brood Atlantic salmon reared to maturity in saltwater net pens in Puget Sound, Wash.

Conclusions

Atlantic salmon can be reared successfully in Pacific Northwest waters using techniques employed for rearing Pacific salmon, including the recently developed net pen culture systems in salt water. There appear to be no adverse factors in the rearing cycle that cannot be controlled with known fish cultural techniques. The mild temperatures in the area are conducive to production of yearling smolts. Saltwater rearing posed no particular difficulty; adult fish ranging from 2.5 to 5.0 kg (from 5.5 to 11.0 pounds) and from 5.1 to 9.0 kg (from 11.2 to 19.8 pounds) were produced at 4 and 4.6 years of age, respectively. Adult fish produced viable eggs and sperm; they had a subsequent hatch rate of over 80 percent.

Literature Cited

Bams, R. A., 1973. Evaluation of gravel incubators on first "hatchery" generation Tsolum River pink salmon, 1970-1972; Part I: Evaluation at the fry stage. Fish. Res. Board Can., Tech. Rep. 364, 18 p.

Colton, J. B., and R. R. Stoddard, 1972. Average monthly seawater temperatures, Nova Scotia to Long Island, 1940-1959. *In* Serial Atlas of the Marine Environment, Folio 21. Am. Geogr. Soc., N.Y.

Elson, P. F., 1957. The importance of size in the change from parr to smolt in the Atlantic salmon. Can. Fish-Cult. 21:1-6.

Hodgins, H. O., M. H. Schiewe, A. J. Novotny, and L. W. Harrell, 1977. Pacific salmon disease-General. *In* Carl J. Sindermann (editor), Disease diagnosis and control in North American marine aquaculture, p. 227-230. Elsevier Sci. Publ. Co., Amsterdam.

Huet, M., 1972. Textbook of fish culture. Breeding and cultivation of fish. Page Bros. (Norwich) Ltd., Norwich, 436 p.

Leon, K. A., 1975. Improved growth and survival of juvenile Atlantic salmon *Salmo salar*, hatched in drums packed with a labyrinthine plastic substrate. Prog. Fish-Cult. 37(3): 158-163.

Netboy, A., 1968. The Atlantic salmon; a vanishing species? Houghton Mifflin, Boston, 457 p.

Novotny, A. J., 1975. Net pen culture of Pacific salmon in marine waters. Mar. Fish. Rev. 37(1):36-47.

Van Duijn, C., Jr., 1967. Diseases of fishes. Cox, Wyman, Ltd., London, Reading, England, 309 p.