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Net-Pen Culture of Pacific Salmon in Marine Waters

ANTHONY J. NOVOTNY

ABSTRACT — The concept of floating net-pen culture of fishes in marine waters has been expanded to include Pacific salmon, Oncorhynchus spp., *in the Pacific Northwest. The National Marine Fisheries Service initiated the research in Puget Sound, Wash., in 1969 with small (2.7 m^3) net enclosures. The rapid growth and reasonable survival of cultured coho salmon,* O. kisutch, *led to the development of a pilot farm. The farm utilized a surface area of 0.1 ha with four net pens totaling 7,080 m^3 in volume. A total of 61.4 metric tons (mt) of 170- to 380-g Pacific salmon were shipped to market within 18 mo after fertilization of the eggs. Coho salmon have been raised to maturity in seawater pens in 2- and 3-year cycles. Survival of both brood stocks and fertilized eggs from cultured salmon is variable, however, and improvement is needed in controlling disease and nutrition. Bacterial pathogens are a serious problem. A vaccine for the control of vibriosis, the most prevalent disease, appears to be successful but needs further study and evaluation. Net-pen culture is being practiced in Puget Sound waters for two purposes: (1) the commercial production of pan-sized Pacific salmon by private farms and (2) the extended rearing of hatchery-produced salmon for release to the local sport fishery. Total sales in early 1973 of privately farmed fish were over 40 mt and were expected to rise to 1,800 mt in 1974.*

INTRODUCTION

Pacific salmon, *Oncorhynchus* spp., reproduce in fresh water of the highest quality. Losses of salmon stocks from damming, logging, pollution, etc., coupled with the rising demand for salmon as food, have led to extensive investment in artificial propagation to augment the natural runs. During the last 100 years, salmon hatcheries on the Pacific coast of the United States have evolved into expensive systems under constant economic scrutiny. In many areas rising capital costs and the limited fresh water will prevent much new construction or expansion of salmon hatcheries. Therefore, to expand the present levels of production we must seek new, economical methods of salmon culture.

In the Pacific Northwest, the National Marine Fisheries Service (NMFS) began culturing salmon in floating net pens in 1967. The plans originally called for large-scale culture in the freshwater reservoirs behind the dams on the Columbia River and, by 1969, the concept was expanded to include the marine environment.

The marine culture of salmonids is not new. Rainbow trout, *Salmo gairdneri*, and Atlantic salmon, *Salmo salar*, are being cultured in Scandinavia and the British Isles in seawater (Novotny, 1969 and 1972). Rainbow trout and, to a limited extent, Pacific salmon are being cultured in seawater in Japan (Tomiyama, 1972), (N. Yoshikawa, Japan Marine Photo Studios, Tokyo, pers. commun.). Although some of the culture methods involve ponding, in most of these countries there is some floating cage or net-pen culture.

NMFS research in the marine culture of Pacific salmon is now being

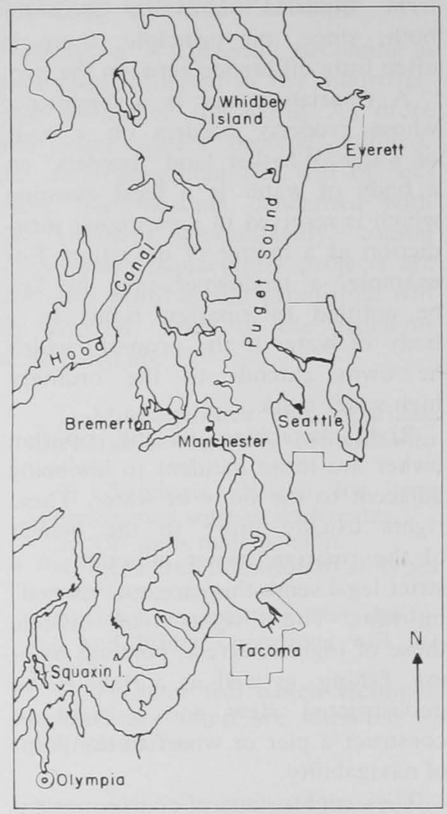

Figure 1.—Puget Sound, Wash. This inland arm of the Pacific Ocean is the site of major activities for the marine culture of Pacific salmon.

conducted at a research station on Clam Bay in Puget Sound near Manchester, Wash. (Fig. 1). This site has the advantages of good water exchange from tidal currents, narrow annual ranges of water temperature (6.5-16°C) and salinity (26-31 ‰), shelter from the wind, depths to 30 m, and a small freshwater stream entering at the head of the bay.

The general objectives of the salmon research at the NMFS Manchester station are: (1) to determine the most economical methods for commercial

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culture of salmon in net pens and (2) to determine the feasibility of modifying migration patterns and improving the survival of Pacific salmon at sea by raising them in net pens before their release. If successful, the latter technique should increase the contribution of artificially reared salmon to sport and commercial fisheries.

Other aspects of the NMFS program involve research on systems for accelerating the freshwater growth, the relation of temperature and ration to growth in seawater, brood stock development, control and prevention of diseases, possible uses of hybrids, development of fish-feed supplements from new resources, and effects of large-scale production in the saltwater environment.

NET-PEN CONSTRUCTION

Experimental Pens

The basic requirements for maintaining net pens in salt water are: (1) some type of surface support such as a raft, barge, ship, or dock; (2) a system for holding the headropes of the net pen above the waterline; (3) a mooring arrangement; and (4) a means of holding the bottom of the pen down and keeping it spread open.

The intensive cultivation of fish requires appropriate concentrations of dissolved oxygen, ranges of water temperature, and removal of waste by-products. In Puget Sound, the necessary water exchange for floating net-pen culture is provided by tidal currents. The effects on net enclosures of currents, fouling, and materials have been thoroughly studied in Scotland and Japan (Milne, 1970 and 1972).

The NMFS salmon culture research at Clam Bay began with a base of operations on a vessel moored to a dock. Floats with the top surface the size of a standard sheet of plywood (1.2 × 2.4 m) were filled with Styrofoam[1] billets. The floats were linked together with cable to provide a perimeter enclosure for hanging the net pens and a walkway for conducting work safely. The first pens were actually cages, made of lumber frames with rigid polyethylene plastic screening. These cages were expensive and too heavy for one man to lift. At high stocking densities, contact with the mesh caused scarring of the eyes of the fish and eventual blindness.

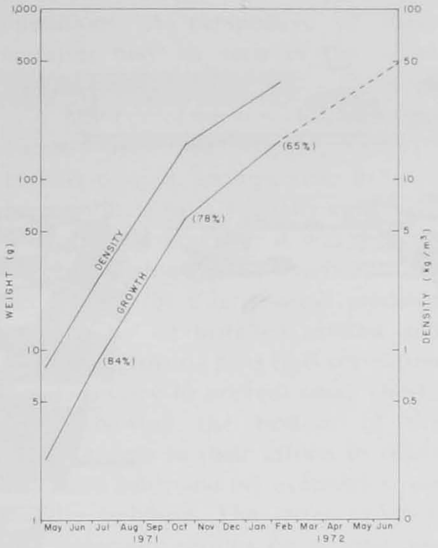

Figure 2.—Growth, rearing density, and survival of hybrid Pacific salmon (♀ *O. tshawytscha* × ♂ *O. gorbuscha*) in a small floating net pen. Pen volume is 2.7m³. Percentage of survivors is in brackets and the broken line indicates frowth after transfer to a larger pen.

We then experimented with knotless nylon pens, 1.2 × 1.8 × 1.2 m. The net pens were hung between the floats and covered with black plastic. Rectangular frames were built from polyvinyl chloride pipe and filled with sand. These frames were dropped into the nets to hold the bottom open and weight the pens down. The black covers inhibit marine plant growth. Fouling occurred from marine animals but did not inhibit water exchange. These small pens were intended for use with small numbers of experimental fish. But, in one case, a group of salmon was reared at a high density to "pan-size" with reasonable survival (Fig. 2).

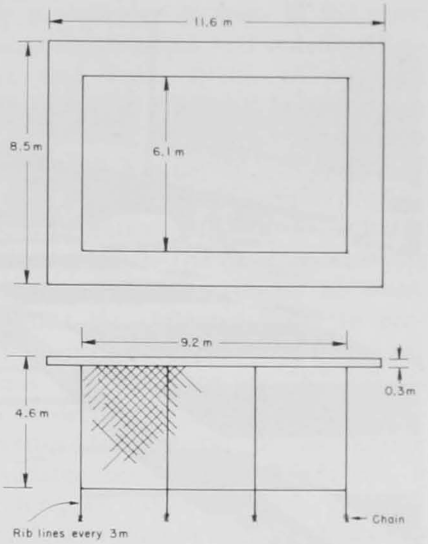

Figure 3.—An experimental production raft and net pen. Raft construction is of lumber, plywood, and Styrofoam billets. Pen volume is 258m³, and production capacity is approximately 4,000 kg of salmon.

The superior performance of the knotless nylon webbing prompted us

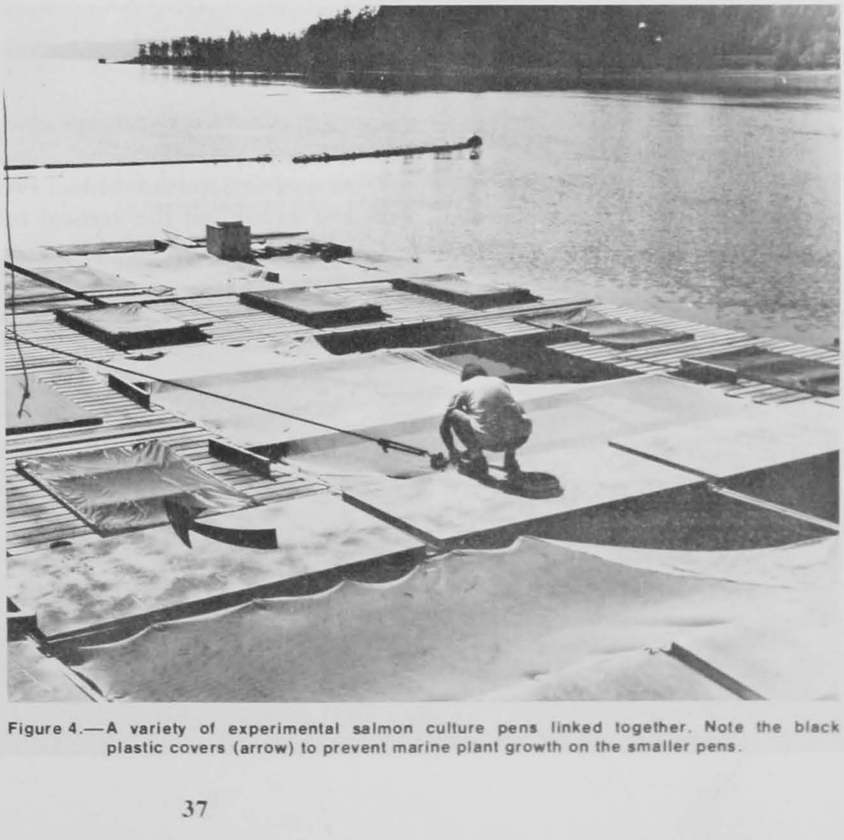

Figure 4.—A variety of experimental salmon culture pens linked together. Note the black plastic covers (arrow) to prevent marine plant growth on the smaller pens.

[1]Mention of trade names does not imply endorsement of commercial products by the National Marine Fisheries Service, NOAA.

Figure 5. — Large rafts for future salmon culture experiments, ready for launching. The rafts have $5 m^2$ openings. They are constructed of Styrofoam-filled culvert material for floatation, soft iron superstructure, and heavy wood decking. They can be bolted together to form a large perimeter enclosure, from which a production net pen can be suspended.

to design larger net pens for growing larger numbers of fish and eventually for raising the fish to maturity (Mahnken, Novotny, and Joyner, 1970; Novotny and Mahnken, 1971 and 1972). Several sizes were constructed, either square or rectangular, the largest of which is shown in Figure 3. The annual production from this pen would be about 4 mt of salmon at a loading density of 15.5 kg/m^3. The capital investment for this raft is less than $0.50/kg of fish produced. The smallest complete raft-pen system that we have used holds a 2.7 m^3 net pen, with a total cost of $80-100 per unit (Fig. 4).

A new experimental raft system was constructed in 1973 (Fig. 5). The units were designed to provide minimum maintenance and "break-down" construction, which is essential for the small staff at the station, and they should last many years.

Staff engineers of the NMFS Northwest Fisheries Center have also designed and constructed two floating hexagonal pen frames of all aluminum construction for the Manchester station (Fig. 6). The frames are similar to those used in Scotland (Milne, 1972) with one exception: the vertical tube members are sealed at the top and bottom and have fill pipes and air-hose connections at the top. When water is blown from the tubes, the frame has a draft of less than 1 m. The frame can then be towed to the beach on a high tide, and the net is installed on the next low tide. The entire net pen is floated on the next tide and towed into its mooring position. The tubes are filled with water until the net pen reaches the desired level. When used at the surface level (a draft of 3.7 m), the net pen has an approximate volume of 220 m^3 and an annual production capacity of 2.5-3.0 mt of salmon averaging 0.3 kg. Theoretically, this unit can even be used submerged when fitted with a special tight-fitting mesh cover (we have tested a completely enclosed cage of knotless nylon (2.8 m^3) in a successful experiment to rear coho salmon under the sea.

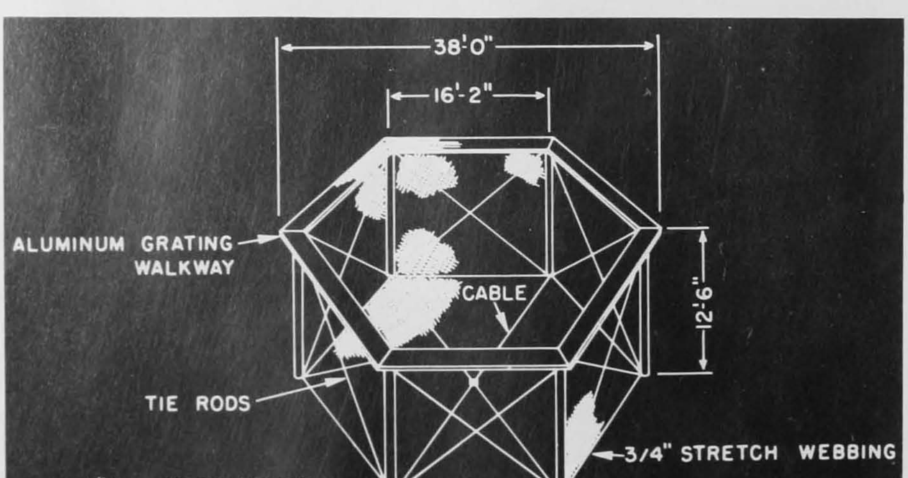

Figure 6.—An experimental hexagonal pen of aluminum construction. The head rope of the net enclosure is hung from aluminum hooks on the walkway. Six rib lines extend through the bottom and pass through pulleys at the foot of each tube. This method permits the bottom and sides to be drawn taut without weights (dimensions are listed in feet and inches).

Commercial Pens

The applications of net-pen culture to commercial production of salmonids pose different problems. Although the factors discussed previously still apply, there are additional considerations, especially economic ones. The cost per cubic meter of growing space is considerably less for larger than for smaller net-pens. Similarly, the cost for perimeter surface support is less for large pens than for a number of smaller pens holding the same volume. However, one must carefully consider the problems of maintenance, current stress forces, and the ability to inventory or harvest fish with a minimum of difficulty. It is doubtful if there is any one unique system that is completely satisfactory, and a need exists for serious engineering tests and cost analysis.

In 1970, the NMFS began a commercial pilot farm study in cooperation with the National Oceanic and Atmospheric Administration's Office of Sea Grant and Ocean Systems, Inc. (now Domsea Farms, Inc.). The pilot farm was designed to produce a maximum of 91 mt of marine-reared Pacific salmon.

The basic raft support structure and main growing pens were designed early in 1971, and the installation in Clam Bay was completed and ready to receive fish in June 1971. The support raft was constructed of welded steel pipe approximately 0.45 m in diameter, heavy "I"-beam cross bracing, and decked with wood. Overall dimensions of the raft were 7.6 × 30.5 m. The raft was towed into position and anchored from the four corners with heavy anchors, chain, and steel cable. Water depth under the raft was about 12 m at high tide and 7 m at low tide.

Four net pens were attached to this raft. The webbing was of 126 denier knotless nylon, with 10 mm^2 meshes. The size of the opened nets was 15.2 m^2 × 7.6 m deep, with a calculated volume of 1,770 m^3. In the interest of economy for the pilot farm study (i.e., the net pens were intended for only 1 year of use), a simple perimeter support system of vertical plastic pipes and Styrofoam cylinders was used. The bottom of the net pen was weighted down by lengths of chain (18 kg each) tied to vertical rib lines. The nets were held open against the changing currents by counterweighted floats attached to the outside surface corners. The entire system is presented in detail in a report on the pilot farm operation[2]. A perspective of these facilities may be seen in the aerial view in Figure 7.

A number of serious problems occurred with this system: (1) the counter-tension arrangement did not keep the nets from partially collapsing in strong currents; (2) it was difficult to keep tension on the overhead bird-net covers; (3) a large-mesh predator net had to be installed around and under the growing pens (this correction was necessary to prevent small sharks from chewing the bottom of the growing pens in their efforts to reach any dead fish); and (4) excessive stress on the webbing. The latter problem was especially serious on at least one occasion. A stress tear occurred in an upper outside corner of the growing pens. The torn section was less than 1 m from the surface, running approximately 0.25 m along the vertical and less than 1 m along the horizontal. Unfortunately the tear was in the highest density pen (estimated at that time to be in excess of 15 kg/m^3)—and before the opening was discovered, an estimated 70,000 marketable fish escaped.

The first large net-pen enclosure used in Puget Sound for holding adult salmon was supported at the surface by a perimeter of floats of the same basic design as our first systems (Hunter and Farr, 1970). In southern Puget Sound, the Small Tribes Organization of Western Washington (STOWW) is applying this system of net-pen support for a salmon production operation adjacent to Squaxin Island (Fig. 1). The basic unit consists of a rectangular perimeter of floats, divided by additional floats to provide surface support for three net pens. The net pens are 18.2 m^2 × 3 m deep; they are protected at the bottom from sharks by an outside predator net. Each net pen has a volume of 1,000 m^3. Early in 1973, 41.8 mt of chinook salmon, *O. tshawytscha*, were harvested from these three pens. The average loading density was 13.9 kg/m^3.

On the basis of our experience thus far, several basic prerequisites would apply to all net-pen culture:

(1) If a mesh size approximating 5 mm^2 or smaller is required for the initial stages, it is far better to use many small units than one large one. Vegetative fouling occurs rapidly and restricts the movement of water through the pens.

(2) Substantial perimeter surface support is required. This is especially true for larger net pens. Wide perimeter flotation will provide:

(a) some protection from waves

(b) protection from surface debris

(c) support for the net pens

(d) safe working areas for broadcasting feed, installing and removing net pens, harvesting, etc.

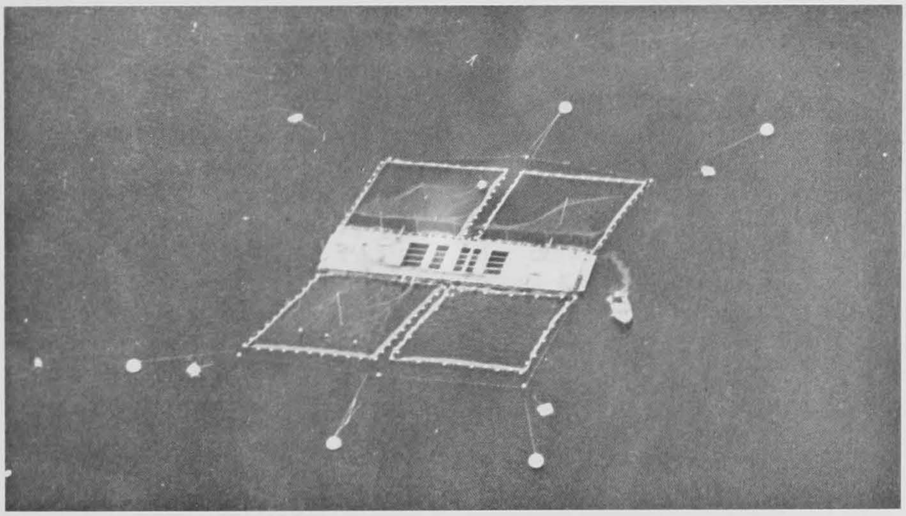

Figure 7. — Aerial view of the pilot salmon farm. Total volume of the four net pens is 7,000m^3. Market harvest from the 0.1 ha of enclosures was 61.4 mt of Pacific salmon.

[2]Lindberg, J. M. [Undated.] Pacific salmon aquaculture program: Incubation and cultivation phases. Sea Grant rep. COM-73-10560, 52 p., App. A-C (Processed). Available at $3.00 per copy from D83, Technical Information Division, Environmental Science Information Center, NOAA, Washington, DC 20235.

(e) a base for bird-net covers
(f) support for winches and other mechanical aids

Although it may cost more per unit volume for smaller net pens than for larger ones, there is a substantial element of risk in large units. The old adage about "putting all of your eggs in one basket" is appropriate for net-pen culture in open waters. In my estimation, the maximum size of a production unit should be about 15 m^2 $\times$ 4 m deep.

GROWTH OF SALMON IN SALTWATER PENS

During the course of our studies, we made comparative growth measurements of the Pacific salmon in floating net pens—some species were studied more comprehensively than others. Five species of Pacific salmon studied, in order of increasing intensity, are: sockeye salmon, *O. nerka;* hum salmon, *O. keta;* pink salmon, *O. gorbuscha;* chinook salmon, and coho salmon. Chinook and coho salmon are now the fish of interest in our region.

Water temperature has a great influence upon growth, as do photoperiod, dissolved oxygen, nutrition, disease, and size at entry into salt water. A degradation of any one of these factors can reduce the rate of growth, which is essential for commercial production.

Fall spawning chinook salmon are cultured in most State and Federal hatcheries in Washington and Oregon. In most years, State hatcheries have surpluses of chinook eggs, but this availability is not reliable due to occasional low returns. Fall chinook salmon adapt to seawater in the first spring or summer of their life (zero-age fish). The young fish are generally reared in the hatcheries for 90-120 days after they begin feeding. They are then released into the rivers weighing 4-6 g each. Most of the releases are in late May, and the fish migrate rapidly to sea. Hatchery stocks generally return as adults after 3-4 years at sea, and range in size from 3 to 12 kg.

Fall chinook salmon have certain distinct advantages for marine pen culture. The progeny can be transferred directly to saltwater pens in the spring, which would allow greater production from hatcheries with restricted space and water flow. In southern Puget Sound, healthy chinook salmon should weigh 400-500 g within 12 mo after they enter salt water. At our Manchester station, in middle Puget Sound, the annual variations in temperature are not extreme, reaching a low of 6-7°C in late February and then rising slowly to 15-16°C in late August (Fig. 8). In most of our experiments with chinook salmon, they have been introduced to salt water in late May or early June. In general, we found that the slope of the growth curve is similar for different stocks during the summer and winter and from year to year. The salt water growth depends on the size at entry into salt water (Novotny, 1972). For example, if we begin at the same time with two stocks of chinook salmon weighing respectively 5 and 12 g, the growth curves will simply parallel each other, and during the first year the smaller stock will never catch up to the larger one.

Fall chinook salmon weighing 2 g can be acclimated to salt water by incremental increases in salinity (Kepshire and McNeil, 1972); however, few growers are fortunate enough to be situated where they can mix fresh and salt water readily. Most of them move their fish to saltwater pens from a distant hatchery. The tributary streams of Puget Sound warm up faster between April and late June than the waters of the Sound. Since growth can be stimulated by rising water temperature and increasing photoperiod, it can be advantageous for the grower to rear his fish in the warmer fresh water and delay transferring them to salt water until late June or early July. The timing will differ for each farm operation depending on its location.

For commercial saltwater rearing, there are several difficulties with chinook salmon. First, during their first year in salt water, their scales are very loose. This increases the risk of bacterial infection and is a disadvantage in marketing. Secondly, growth and survival have been poor on commercially available dry diets. A diet of Oregon moist pellets (OMP) produces good growth in chinook salmon but requires refrigeration for storage. The rising cost of fish meal has increased the price of pelleted diets. This, coupled with the high cost of freezer storage and less efficient conversion, will probably discourage expanded commercial culture of this species. A most critical problem with chinook salmon is that they do not resist disease as well as coho salmon. I have mentioned in this paper that the STOWW project near Squaxin Island harvested 41.8 mt of chinook salmon from their floating net pens in 1973; although food conversion ranged from 1.8:1 to 2.4:1 on a diet of 85

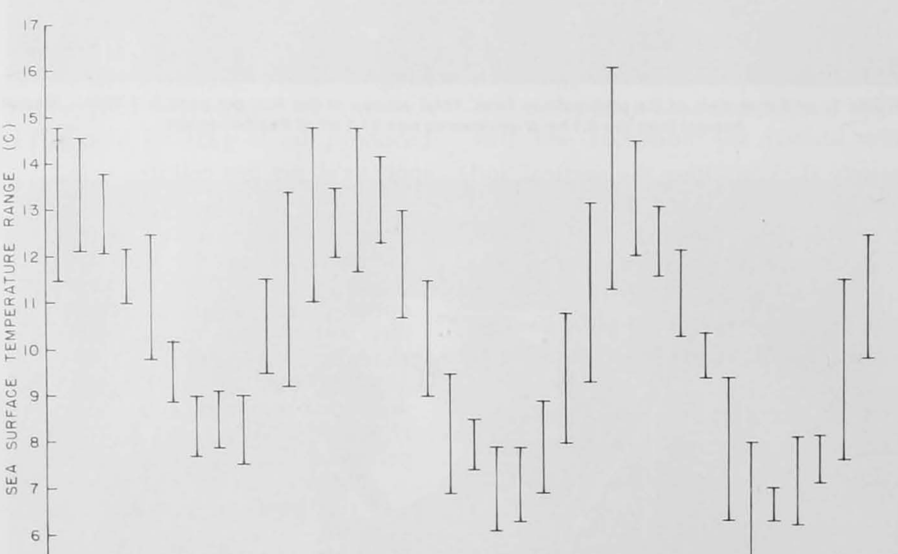

Figure 8.—Records of maximum and minimum monthly sea surface temperatures at Clam Bay, near Manchester, Wash.

percent OMP and 15 percent shrimp waste (for flesh coloring), the overall survival was only 53 percent (Fraser, J., pers. commun.).

Research and development in salmon culture has been largely focused on coho. Most of the state hatcheries around Puget Sound maintain good runs of coho. Under present management practices, there is generally an annual surplus of at least 10 million eggs. The State of Washington recently passed legislation allowing the Department of Fisheries to sell excess coho eggs to commercial growers. Other legislation provides guidance in the establishment of commercial farms. Total capital investment for private salmon farming in Puget Sound is now in excess of $2,000,000.

Puget Sound coho normally spend 1 year in fresh water, migrating to the sea in their second spring. They spend 1 winter in the ocean and return the following fall as mature adults weighing from 2 to 8 kg. The usual hatchery practice is to collect the eggs from returning adults in November-December and release yearling smolts weighing 18-30 g in their second spring. The young coho are fed either OMP or dry diets.

Studies at the NMFS Experiment Station at Manchester indicated that yearlings placed directly into salt water in July, weighing 22 g and fed OMP, would grow at a rate of 2.2-3.3 percent of their body weight per day until fall, with food conversion ranging from 1.4:1 to 3.6:1. Growth rate and food conversion fell during the winter. One year after culture in salt water, the fish ranged from 500 to 1,500 g (Mahnken, Novotny, and Joyner, 1970). We also found that coho yearlings placed in our colder salt water in the spring weighing 10-12 g did not grow as well as larger yearlings, and mortality was higher. Those that survived to maturity weighed from 600 to 2,700 g. From these experiments, we concluded that if coho were reared to 16-20 g in fresh water and placed in salt water during the peak of the photoperiod, they would continue to grow well until harvest.

We tested this on a pilot scale, heating the water as necessary to hold the temperature between 11 and 14°C during egg incubation and rearing of the fry. The fish were fed a dry, pelleted diet. The objective of shortening the typical hatchery cycle by 9 mo was partially accomplished in July, when at least 50 percent of the stock weighing at least 16 g were placed directly into saltwater. The remaining coho were put into saltwater in August. Those weighing at least 16 g continued to grow well. The smaller ones reverted to a presmolt condition and either died or did not grow again until the following spring (Novotny and Mahnken, 1972). It appeared from this that the growth and survival of coho in salt water culture are dependent on their size and whether the photoperiod is increasing or decreasing at the time of their introduction to salt water.

Figure 9 shows the growth of accelerated coho during their first year in salt water compared with that of chinook and pink salmon. In fresh water, food conversion for accelerated coho fed on a dry diet was approximately 1.5:1. Market size (150-300 g) can be attained within 15 mo after fertilization of the egg in November. Year-old accelerated coho will weigh as much as 2-year-old, nonaccelerated coho. The cost of accelerating the freshwater rearing by 9 mo is more than compensated for by savings in feed, labor, and time to market.

DISEASES OF SALMON CULTURED IN SALT WATER

For salmon farms to be successful, survival to market must be improved. In our early studies, we found that with coho salmon reared at low densities, mortality ranged from 1 to 3 percent per month for the first year,

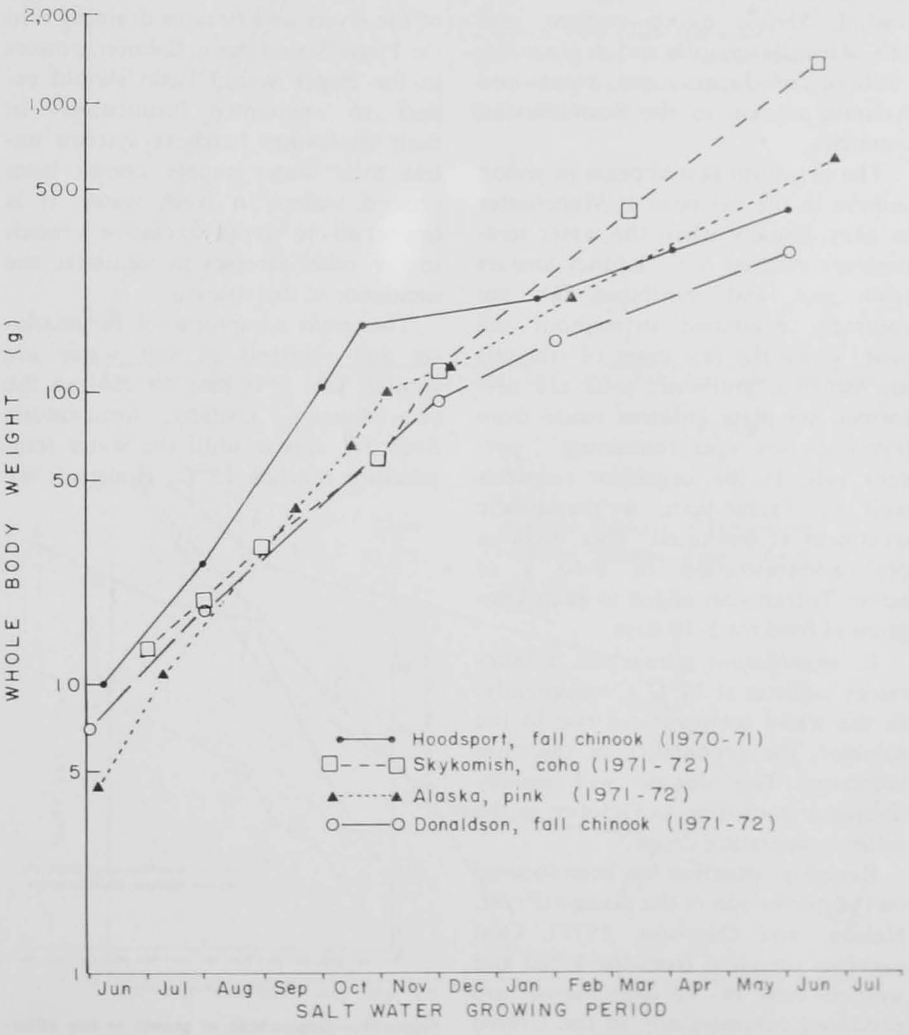

Figure 9.—Growth of three species of Pacific salmon during 1 yr in salt water. Differences between growth of the two stocks of chinook salmon (reared in different years) are believed due to differences between size at entry to salt water, water temperature, and disease influences.

the highest occurring in the summer. This would not be unacceptable. Even at high densities (Fig. 2), survival of a hybrid less hardy than coho was 60-65 percent.

The mortalities of Pacific salmon cultured in the sea are usually due to bacterial diseases. Although microbial organisms other than bacteria have been suspected as pathogens in some cases, the incidences are not frequent.

Bacterial diseases of marine fish are a worldwide problem (Sindermann, 1970), but the problems associated with the large-scale production of Pacific salmon in salt water have only recently been reported (Novotny and Mahnken, 1971). The organism that causes the greatest concern is the gram-negative, motile, comma-shaped rod, *Vibrio anguillarum*. This is the same bacterium that has been reported to cause extensive mortalities in yellowtail, *Seriola quinqueradiata*, and eels, *Anguilla anguilla* and *A. japonica*, cultured in Japan, and trout and Atlantic salmon in the Scandinavian countries.

The organism first appears in young salmon in the net pens at Manchester in May, usually when the water temperature reaches 9°C. Kidney smears from sick and moribund fish are routinely examined throughout the year. When the first cases of vibriosis are isolated, antibiotic tests are performed on plate cultures made from trypticase soy agar containing 2 percent salt. If the organism responds well to Terramycin, a therapeutic treatment is instituted. This involves oral administration of 8-10 g of active Terramycin added to each kilogram of food for 5-10 days.

V. anguillarum grows best in laboratory cultures at 24°C. Consequently, as the water temperatures rise in the summer, the probability of infection increases. The disease will usually disappear sometime in October as the water temperature drops.

Recently, attention has been focused on the prevention of the disease (Fryer, Nelson, and Garrison, 1972). Oral vaccines prepared from the killed and washed cells of *V. anguillarum* are produced commercially in the United States. The vaccine is added to the diet and fed to the young salmon prior to putting them into salt water. Oral vaccines were first used by commercial salmon farms in 1973, and the results of the field trials will not be known for some time. Laboratory experiments indicate that the oral vaccine probably becomes localized in the intestinal tract and does not provide as much protection as direct injections of the killed cells into the body cavity. A great deal of research remains to be conducted on vibrio vaccines, but I have no doubt that within the next 5 years routine vaccination against this disease will be standard procedure in salmon farming.

Furunculosis, a disease caused by a gram-negative, nonmotile bacterium, *Aeromonas salmonicida*, is also a serious problem. Pen-cultured Pacific salmon usually become infected with the organism in fresh water and carry it with them into salt water. This organism is common in most of the rivers and streams draining into the Puget Sound basin. Salmon growers in the Puget Sound basin should expect to encounter furunculosis in their freshwater hatchery systems unless their water supply comes from ground water. In fresh water, it is important to avoid excessive crowding or other stresses to minimize the incidence of this disease.

The gross symptoms of furunculosis and vibriosis in salt water are similar, and it is easy to confuse the two diseases. Usually, furunculosis does not appear until the water temperature reaches 12°C. However, we have noted that the physiological stress produced by transferring fish directly from fresh into salt water will sometimes stimulate the disease at lower temperatures. The two diseases sometimes occur simultaneously. Since the therapeutic treatment may be different for each disease, plate-culture tests should be conducted to distinguish the two organisms. *A. salmonicida* will color tryptose blood agar brown within 2-5 days at 24°C.

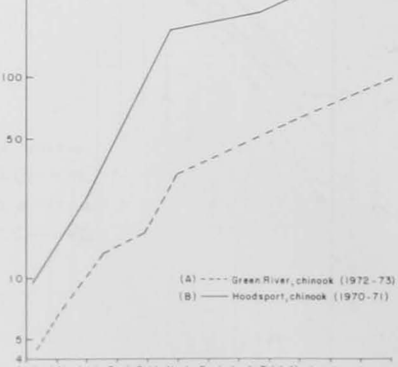

Figure 10.—Comparison of growth in two different stocks of chinook reared at Manchester during different years. Stock A suffered serious disease problems.

We found that *A. salmonicida* is transmittable at 30 ‰ salinity, and we isolated it from a diseased eulachon, *Thaleichthys pacificus*, found in the net pens with infected salmon. The organism can be grown on tryptose blood agar at 30 ‰ salinity, although pigmentation is better at 20 ‰. We found that local strains of this bacterium do not respond to sulfa derivatives when tested on Mueller-Hinton's agar and do not usually respond to Terramycin in blood agar. The furunculosis organism is inhibited by Chloromycetin, nalidixic acid, and the furinase compounds. Furox 50 (containing 11 percent active furazolidine) was effectively used to treat a large number of young fall chinook salmon in saltwater pens suffering from an epidemic outbreak of furunculosis. A level of approximately 40 g of Furox 50 per kilogram of food was used for 10 days. Prior to this treatment, over 90 percent of the fish died from either vibriosis or furunculosis over a 7-mo period.

Uncontrolled disease outbreaks adversely affect growth as well as survival. Figure 10 is a comparison of the growth of the aforementioned stock of chinook salmon with an earlier year class that was not infected. Note the extremely poor growth of the diseased stock during the late summer and early fall.

Kidney disease is a chronic bacterial infection that prevails during the winter. The causative agent is a gram-positive, nonmotile bacterium thought to be of the genus *Corynebacterium*. It does not usually occur in young fish until their first winter in the saltwater pens and is a serious problem with brood stock at any time of the year. There are no effective therapeutic agents that are known to us. Treatments with penicillin have

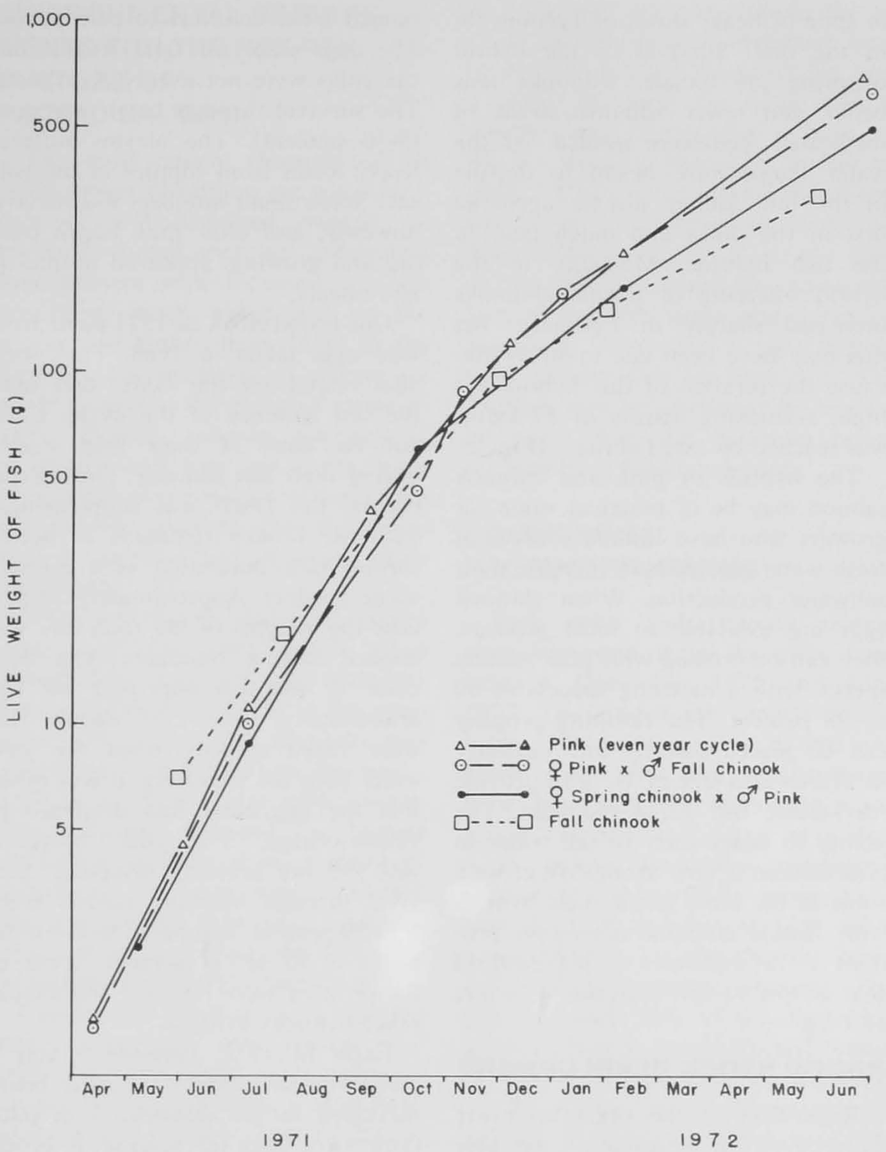

Figure 11.—Comparison of growth of pink and fall-chinook salmon (1970 brood year) reared in saltwater pens near Manchester, Wash. Two hybrids are included in the comparison.

been partially effective but only to the extent that the disease is temporarily arrested.

POSSIBLE USES OF HYBRIDS

A number of biological variations can be found in the five species of Pacific salmon common to the west coast of North America, such as salinity adaptation, temperature preference, growth, disease resistance, and maturation cycles. Although most interspecific hybrids of Pacific salmon are sterile, information from experimental hybridization has practical as well as scientific value. For example, pink salmon can adapt to high-salinity water almost immediately after they begin feeding, whereas chinook salmon cannot. Pink salmon also grow faster in the winter than chinook salmon. Pink salmon mature in 2 years compared to 3-5 years for chinook salmon.

Figure 11 is an example of the comparative growth of pink and chinook salmon and of reciprocal hybrids of the two species. In this case, the chinook female donor was of a spring-run race. Spring chinook juveniles normally spend 1 year in fresh water and migrate at a size of 30 g or more. Fall chinooks migrate to sea weighing 5-10 g in the late spring or summer before the end of their first year. Note that the rate of growth of the pink salmon and the hybrids exceeded that of the pure fall chinook salmon and that both hybrids were capable of entering salt water early in the season and at a small size.

Disease resistance also differs. The pink salmon that we reared have been extremely susceptible to vibriosis, furunculosis, and kidney disease. When reared under similar conditions, the hybrids of pink and chinook salmon respond differently to these diseases (Fig. 12). In this case, pinks and the reciprocal hybrids of chinook and pink salmon were placed in adjacent net-pens at approximately the same density. The first diseases to occur were vibriosis and furunculosis during spring and summer. The pinks and hybrid offspring of female pinks died at about the same rate until fall,

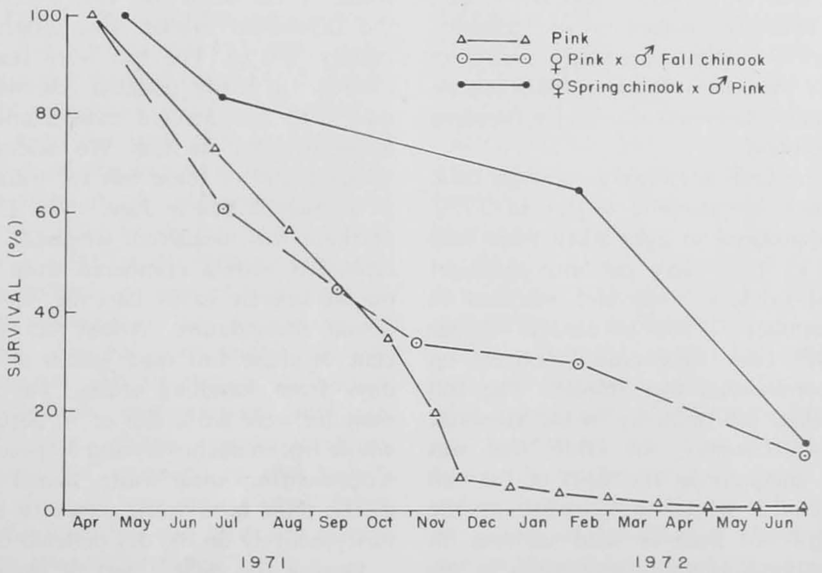

Figure 12.—Survival of Alaska pink salmon (1970 brood year) and two hybrids reared in saltwater pens near Manchester, Wash.

in spite of heavy doses of Terramycin in the diet. Survival of the hybrid offspring of female chinooks was better and fewer administrations of medicated feed were needed. As the water temperature began to decline in the fall, kidney disease appeared first in the pinks and much later in the two hybrids. Mortality in the hybrid offspring of female chinooks increased sharply in February, but this may have been due to stress. Because the survival of this hybrid was high, a stocking density of 37 kg/m^3 was reached by mid-February (Fig. 2).

The hybrids of pink and chinook salmon may be of practical value for growers who have limited sources of fresh water and wish to increase their saltwater production. When chinook eggs are available to local growers, they can be crossed with pink salmon sperm, with a hatching success of 90 to 95 percent. The resulting progeny can be placed directly into seawater in March at a size of 1-2 g to provide marketable fish 12-14 mo later. The ability to adapt early to salt water in pink salmon is very strong. We crossed some of the more fertile male hybrids with female chinook salmon to produce a ¾ chinook, ¼ pink hybrid that adapts to full seawater at a size of 1-2 g.

BROOD STOCK DEVELOPMENT

Regardless of the organism being cultured, it is desirable to be able to "close the cycle," that is, be able to rear the organism to maturity, have it spawn successfully, and produce healthy progeny. This is extremely important if selective breeding is planned.

Our first attempts at rearing coho salmon to maturity began in 1970. The progeny of eggs taken from wild fish in 1967 were put into saltwater pens in July 1969 and matured in December 1970, a normal 3-year cycle. They were reared entirely on a commercial diet (OMP). The fish reached full maturity in the saltwater pens. However, the OMP diet was not adequate as the flesh of the fish remained white in contrast to the bright red flesh of wild salmon, indicating a lack of carotenoids in the diet. This lack of pigment was even more evident in the eggs which ranged from colorless to pale yellow. The eggs were soft and fragile, and the yolks were not evenly distributed. The survival through hatch was poor (5-10 percent). The alevins suffered heavy losses from rupture of the yolk sac. Some small numbers did survive, however, and after they began feeding and growing, appeared normal in all respects.

Our brood stock in 1971 came from wild eggs taken in 1968. They were also reared on the OMP diet until the last summer of the cycle. Coho put on most of their final weight during their last summer. During this period, the OMP was supplemented with the broken remnants of peeled shrimp tails purchased as a cannery waste product. Approximately 30 percent (by weight) of the total diet was cooked shrimp remnants. The flesh color of the fish improved but not dramatically. When the mature fish were taken directly from the saltwater pens for spawning, it was noted that the egg color had deepened to yellow-orange. The yolk, however, was still not properly dispersed. Survival through hatching ranged from 5 to 50 percent, compared to a normal range of 92 to 98 percent. Some of the progeny were retained and should reach maturity in 1974.

Early in 1972, between 5 and 6 percent of the accelerated coho being marketed in the demonstration pilot farm were held for rearing as brood stock. These were fish that exceeded the maximum market size (approximately 380 g). The fish were reared entirely on a dry pelleted Abernathy diet with 0.1 percent canthaxanthin added to color the flesh. We randomly selected 200 of these fish for transfer to a research pen in June 1972. Each of them was measured, weighed, and identified with a numbered strap tag on the opercle or by dart tag in the dorsal musculature. About 6.5 percent of these fish died within a few days from handling stress. The remainder were fed a diet of 70 percent whole frozen anchovies and 30 percent frozen shrimp meat waste. Brood fish in the pilot farm were grown to maturity entirely on the dry pelleted diet.

During the final 3 mo of growth, both groups grew rapidly. Figure 13 is a histogram of the weight ranges of the fish reared in the research pens. During the 92-day period between 15 June and 15 September 1972, the average weight increased by 1,360 g, an average daily weight gain of 14.8 g. The maximum weight of any individual fish on 15 June was 1,950 g and on 15 September, maximum weight was 4,200 g. Although individual fish did not retain either of the two types of tags used to the degree expected, some individual growth records are available. Table 1 shows a selection of fish that retained their tags until they died or reached maturity. Although there is a marked difference in individual growth rates, one item is evident: the maximum weight of the brood coho was achieved during the final summer and leveled off or declined with the onset of fall even though food was available *ad libitum*. The ratio of food conversion during the peak summer growing period was from 4.5 to 5.5:1 on a wet weight basis, or about 5:1. The daily weight gains of identified fish ranged from 5 to 28 g, indicating a daily food intake of 25-140 g of whole anchovies and shrimp meat waste. Although I do not recommend this as a brood diet, it is not expensive. Food costs during this period were approximately $0.16/kg, or $0.80/kg of weight gain during the summer.

Survival during the summer was 73 percent, but prespawning mortality was high. This was primarily due to kidney disease and occurred at a high rate on brood fish reared on the dry diet as well. Brood fish were allowed to mature in the pens and spawned in November-December 1972 as 2-year-old adults. The fertility ranged from 10 to 85 percent, considerably better than in previous years with age-3 spawners. Fertility of the brood coho reared on the dry diet was reported to be in the same range. Reciprocal crosses were made with 3-year-old wild spawners returning from the open sea to our freshwater hatchery to compare sexual fertility. We concluded from this experiment that the infertility problem was with the cultured females.

Brood fish that escaped during the transfer in June 1972 entered Beaver Creek that fall to spawn as 2-year-old fish, and the sizes were approximately

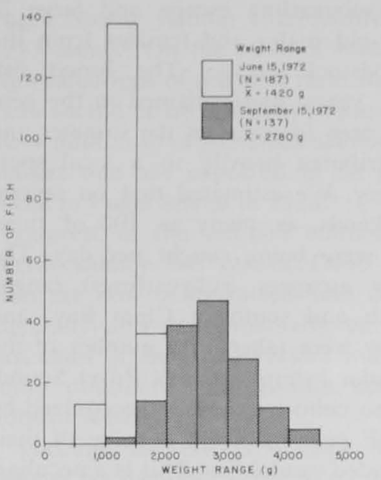

Figure 13.—Frequency distribution of weight range of accelerated coho salmon (1970 brood year) held for brood stock. During the 92-day period prior to spawning (as 2-year-old adults), the average daily weight gain was 15.4 g.

the same as those cultured in the net pens. The range of fertility was the same as for the fully cultured fish, even though they had at least 3 mo of active feeding in open waters. I can only deduce that the nutritional requirements for brood fish must be met much earlier in the life cycle than we anticipated, probably within 12 mo after swim up. This has serious implications for those farmers who want to culture brood stock. The cost of coho eggs to the growers is $6-10 per 1,000 eggs. Average fecundity of the 1972 brood of 2-year-old adult female coho was over 3,000 eggs. Thus, the value of the best brood females may be in excess of $30 each. Survival and fertility of these fish will be critical factors in the economics of brood-fish farming.

Table 1.—Growth records (1972) of individual accelerated coho salmon in the last phases of their 2-year life cycle.

Fish Number	Date of Measurement	Fish weight	Weight increase Total	Per day
		Grams	*Grams*	
1	6-15	1,570	—	—
	9-15	4,150	2,580	28.0
	10-31	4,450	300	4.9
2	6-15	1,950	—	—
	9-15	4,200	2,250	24.5
	10- 6	4,000	−200	−9.5
3	6-15	1,650	—	—
	9-15	3,500	1,950	21.2
	11- 5	3,550	50	0.98
4	6-15	1,500	—	—
	9-15	3,600	2,100	22.8
	11- 5	3,450	−150	−2.9
5	6-15	1,480	—	—
	9-15	3,200	1,720	18.7
	9-27	3,080	−120	−10.0
6	6-15	1,400	—	—
	9-15	2,200	800	8.7
	11-27	1,760	−440	−6.0

ENVIRONMENTAL REQUIREMENTS FOR THE NET-PEN CULTURE OF PACIFIC SALMON

The most critical elements of the environment of salmon are water temperature and dissolved oxygen. In the Puget Sound area, we recommend that growers seek locations that do not range much below 8°C in the winter nor higher than 16°C in the summer. The problems of disease are much greater at the elevated temperatures. Studies relating temperature to growth and feed conversion have been conducted for several years and will provide growers with the information necessary to optimize their operations.

We found that the dissolved oxygen content of the open water varies considerably during a day. Monitors were suspended for 24 hr in the open water and in a 10-m diameter pen with 7 mm^2 mesh openings containing 8-10 kg of salmon per cubic meter. The difference between the highest and lowest concentrations of dissolved oxygen of the open water for that day was greater than any instantaneous difference between the open water and the inside of the pen full of fish.

Commercial farms in Puget Sound have occasionally experienced relatively low concentrations of dissolved oxygen in large net-pens during slack tides. Some of these pens are 20 m^2 or larger with fish densities up to 16 kg/m^3. The constant swimming of the fish creates currents that force new water through the pens. However, there are limits to this type of exchange. We have not been able to undertake studies of the practical limits of net-pen sizes at our experiment station, but we plan to do so in the future.

The effects of high-density net-pen culture on the environment are being studied at our station. In the water, the net pens present a substrate for the attachment of various species of macrophytes, molluscs, and other marine organisms. Crustaceans are attracted to the growth, and these in turn attract small fishes. Predatory fishes and birds are attracted by the smaller fishes.

The sea floor beneath the pens has attracted flatfishes and several species of crabs and echinoderms. In the vicinity of the net pens that have been in use for research purposes for over 4 years, we have not been able to observe any detrimental effects on the sea bottom. However, in the vicinity of the pilot farm operations, the effects of overfeeding were evident. The deposition of excess food on the bottom created an undesirable habitat for both fishes and sedentary organisms. Recovery of the bottom to its natural state has been slow. The problem can be alleviated by feeding no more than the optimum ration for growth or food conversion.

COMMERCIAL PRODUCTION FARMS

Both coho and chinook salmon were harvested from the pilot farm between December 1971 and June 1972. The graded fish ranged in size from 170 to 380 g. One of the purposes of the pilot farm was to determine how well the restaurant trade would respond to salmon at a size never before available—comparable to that of commercially grown rainbow trout. A number of U.S. cities were selected for the market tests, and in most cases the wholesale distributors were able to sell the small salmon (dressed, heads on, and frozen in individual packages) for $3.85/kg. In the future, Puget Sound salmon farmers who take advantage of the experience gained in the pilot farm and make the necessary engineering corrections should have little difficulty in supplying premium quality fish to a growing market (both national and international) at a profitable price. Marketable fish (0.25 kg each) can be grown at a rate of 1-5 million fish/ha/yr (depending on the depth of the net pens). Thus, it will take very little surface area to supply current market demands.

The complete accelerated growth cycle of the coho salmon from the pilot farm study is shown in Figure 14. Note that the time from first feeding to market for "pan-sized" fish is less than 18 mo. Larger fish could be grown in less than 2 years if a market should develop. At the present time, Japanese yellowtail are the only cultured marine species that can match

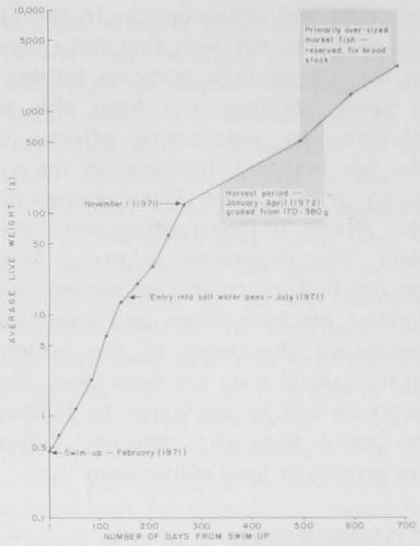

Figure 14. — Accelerated growth of coho salmon from the 1970 brood of Skykomish River hatchery stock.

the rate of growth and rearing densities of coho salmon in net-pen culture (Novotny, 1972).

Although the number of coho shipped to market was only slightly more than 10 percent of the number of eggs taken, a large portion of the loss was due to correctable engineering problems. Recent forecasts based on well-designed systems indicate a harvest of over 60 percent from the swim-up fry stage.[3] In one experiment, we were able to rear 70,000 coho from the fertilized egg to smolt size with over 95 percent survival. Moreover, coho smolts injected with a vibrio vaccine survived the critical spring and summer months (including biweekly handling for growth measurements) with over 95 percent survival, with no antibiotic treatments. I see no difficulties in projecting a survival of greater than 80 percent from the fertilized egg to market stage in the next 5 years.

ENHANCEMENT OF SPORT FISHERIES

Puget Sound, as an inland arm of the sea, is an idyllic marine recreation area for much of the year (including the winter). It is especially appreciated by sport fishermen who like to fish for coho and chinook salmon. Unfortunately, most of the hatchery-reared fish of these species migrate out through the Sound to the open sea and are unavailable to the sport fisherman except for a short time during their return as adults.

Biologists of the Washington State Department of Fisheries (WDF) found that if they delayed releasing their fish until early summer, most of the salmon would establish residency in the Sound and become available to the sport fishery on a year-round basis. However, since hatchery capacities are limited in the number of pounds of fish that can be produced, this problem could be alleviated by transferring the fish to saltwater pens and rearing them until the summer or later.

We began a cooperative study with WDF in 1971 to rear over 70,000 coho yearlings from April until July. These fish were obtained from a hatchery in the southern part of Puget Sound. Returns of marked fish from this experiment indicated they were contributing well to the local sport fishery. In the fall of 1972, the mature adults returned to Clam Bay and entered the fish ladder in Beaver Creek. The returns to Beaver Creek were between 0.6 and 1.5 percent of the number released. In Puget Sound, most hatchery returns of coho range from 0.05 to 2.0 percent. Thus, it is apparent that we can alter the migratory behavior pattern by extending the culture into the marine environment. Such a practice could have distinct advantages in fishery management.

A similar experiment in Alaska led to 15 percent returns of coho to the rearing area, allowing for expansion of limited natural freshwater habitats at minimum expense (McNeil, W. J. Auke Bay Laboratory, National Marine Fisheries Service, NOAA, Auke Bay, AK 99821, pers. commun.).

In the fall of 1972, we noted two additional groups of coho entering the Beaver Creek fish ladder. These were identified (by means of tetracycline marks in the vertebrae produced by antibiotics in the feed) as returns from subyearling and yearling (brood stock) fish that had escaped from the pilot farm experiment. The returns consisted of small 2-year-old males from the subyearling escape and large 2-year-old males and females from the broodstock escape. The brood fish (1+ years) had remained in the general area for most of the summer and contributed heavily to a local sport fishery. We estimated that on several weekends, as many as 100 of these fish were being caught per day. The early escapees (subyearlings) ranged north and south of Clam Bay, and many were taken in a number of the popular fishing areas of Puget Sound. These coho were easily recognized by WDF patrol officers because of their rounded caudal fins. This is a peculiarity of salmon reared in net pens at high density for long periods and is evidently due to abrasion from the webbing.

The return of these two groups of coho to Beaver Creek suggests that there must be a controlling factor of time release or size of fish that determines whether mature adults will return as 2- or 3-year-old spawning fish. The 3-year-old adults from the subyearling fish are expected to return to Clam Bay in the fall of 1973.[4]

Returns to the Puget Sound sport fishery of fall chinook salmon reared 9-12 mo in saltwater pens have been even more encouraging. The recovery of tagged or marked chinook salmon in the sport fishery has indicated a harvest of 15-20 percent of the number released, which is exceptional (Haw, F. Washington Department Fisheries Olympia, Wash., pers. commun.). Chinook salmon released from the net pens have also changed their migratory behavior and not only establish residency in the Sound, but also return to streams closest to the pen-rearing areas.

DISCUSSION

Initial research on the net-pen culture of Pacific salmon in Puget Sound has led to a growing number of commercial and experimental farms. This development has also led to a need for providing the technology that will increase the efficiency of all operations. Potential growth of the industry has been outlined, and an estimated 8-9 million lb of fish food will be used in

[3]Richards, J. A., C. V. W. Mahnken, and G. K. Tanonaka. 1972. Evaluation of the commercial feasibility of salmon aquaculture in Puget Sound: A preliminary analysis. Northwest Fisheries Center, National Marine Fisheries Service, NOAA, Seattle, Wash. 47 p. (Processed.)

[4]A number of large 3-yr-old adults, from these subyearling fish, did return to Beaver Creek in November 1973.

Puget Sound salmon mariculture in 1973 alone.[5] On the basis of marketing evaluations of the pilot farm study, there should be no difficulty in moving the 4 million lb of pan-sized salmon to market that are expected to be produced in Puget Sound in 1974.[6]

Interest in the net-pen culture of Pacific salmon has spread. Coho salmon are now being raised both commercially and experimentally on the east coast of the United States and are being considered for culture operations in Western Europe.

Through the efforts of past technology, we have been able to establish the beginnings of a sound farming system in salt water with the coho salmon. F_1 generations of totally cultured coho will be entering the market in large numbers.

However, a great deal of scientific information relating to salmon biology is needed by growers. We are probably at the same threshold that the poultry industry confronted 50 years ago. The fields of engineering, nutrition, genetics, and disease, along with environmental quality will all apply to salmon farming. The burgeoning problem of finding appropriate protein resources to supply the increasing demands for fish feed cannot be taken lightly. Expansion of this industry will be limited to the technological effort that is applied to it, either by private enterprise or by the government.

[5]True, E. H. 1972. The potential for producing feed for salmon culture in the Puget Sound area. MBA thesis, University of Washington, Seattle, WA 98195, 101 p.

[6]Wagner, L. C. 1972. An evaluation of the market for pan-sized salmon. Prepared for the Marketing Research and Services Division, National Marine Fisheries Service, NOAA, Seattle, Wash. (Res. contract No. N208-0344-72N), 50 p. (Processed.)

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