THE MARINE CULTURE OF VERTEBRATES

By

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INTRODUCTION

There are probably a number of definitions to describe a marine vertebrate. However, for the purposes of mariculture directed toward the production of food, I propose to define a marine vertebrate as "a fish, reptile, or amphibian whose natural history requires that it spend part of or all of its life in the sea or thrive for all or a portion of its life in full sea water." These would include both anadromous and catadromous species of fish. Species that are never (or rarely) found in full sea water, even though they may frequent brackish estuaries, would not be included in this definition. I do not include the marine mammals in the category of culturable marine vertebrates because of the aversion in some parts of the world to their slaughter.

It is difficult to accurately determine the annual production and species composition of vertebrates that are reared in salt water for food because reports from some regions give the total production of cultured fish, which includes fresh and brackish water operations and does not list the harvested species. The main areas of commercial production of marine vertebrates, however, are the Indo-Pacific and Mediterranean regions. Japan, Malaysia, Taiwan, and the Philippines collectively produce many thousands of metric tons of fish each year. Japan is the leading nation in this field and produced 28 thousand metric tons in 1968 (Furukawa, 1971). Japanese "yellowtail" (*Seriola quinqueradiata*) comprised 97.5% of this total. The commercial production in the southern hemisphere is probably quite small.

Newspaper accounts, however, indicate that there are marine projects underway in Australia and in some of the equatorial islands. Production in North American and European countries (other than the Mediterranean region) is also relatively small (probably less than 1,000 metric tons per year). In northern Europe, the major species being reared are salmon and trout of the genus *Salmo*. In the British Isles, for example, rainbow trout (*S. gairdneri*) is the most common species cultivated in salt water. Along the Atlantic coast of the North American continent, Florida pompano (*Trachinotus carolinus*) and *Salmo* spp. are the most common fish being reared. The Florida pompano operations are still in the development stages and nearly all of the Salmonidae are produced in Canadian provinces.

The west coast of the North American continent has virtually no commercial production of marine vertebrates, with one exception--Puget Sound in Washington State. Here, a cooperative government-industry pilot farm in Clam Bay near Manchester has harvested and sold approximately 20 metric tons of cultured coho salmon (*Oncorhynchus kisutch*) and is currently harvesting about the same quantity of chinook salmon (*O. tshawytscha*). The Lummi Indians have also harvested small quantities of saltwater adapted rainbow trout from their facilities in northern Puget Sound near Bellingham.

I found no data on the commercial production of marine reptiles or amphibians for food, and it is doubtful that any production exists. Nonetheless, there is a marine farm in the Caribbean area that is rearing marine turtles. Herbivorous, fecund, and fast growing, these creatures have a high demand and low mortality (when cultured). The marine turtle may prove to be an excellent animal to culture in the Caribbean region.

The present world production of cultured marine vertebrates is very small in relation to the quantity of "wild" fish that are taken from the sea and animals that are reared on land for food. This is particularly true in North America. However, when one considers the great demand in Canada and the United States for high quality, high-priced fish, the potential economic yields of North American coastal waters--a large portion of which is environmentally clean and sheltered--becomes significant. This has been borne out and worldwide interest has been generated by the results of research on Pacific salmon in Puget Sound by scientists of the Northwest Fisheries Center of the U.S. National Marine Fisheries Service (NMFS). Therefore, I will attempt to focus the major portion of this presentation on the results and applications of the NMFS findings and compare them to some other culture activities.

METHODS OF CONFINING MARINE VERTEBRATES

Diked Tidal-gate Ponds

Diked tidal-gate ponds are probably the most prevalent method of confining marine fishes in terms of surface area utilized, but they are not necessarily the most productive. Hickling (1970) estimates that over 392,000 hectares are devoted to brackish-water fish farming, mostly as tidal-gate ponds of one form or another. It is difficult, however, to estimate what proportion of the above area is devoted purely to marine species. Tidal-gate ponds usually have poor water exchange and are frequently designed to be nutrient traps. These features limit the production of species having high metabolic rates or are conducive to the production of herbivorous species, especially in the tropical and subtropical regions.

The eels (Anguilla anguilla and A. japonica), which are highly euryhaline, command a high price, and under ideal conditions will produce over 13,000 kg/hectare (ha) (Hickling, 1970). The yellowtail (S. quinqueradiata) can be produced at a rate of over 3,000 kg/ha in tidal-gate ponds. However, both of these fish are carnivorous and the rate of production will depend on (1) oxygen replenishment, (2) removal of waste products, and (3) disease control. Yields of herbivorous species of fish are notably less (experimental maximum of 1,900 kg/ha in Taiwan with Chanos chanos) but require only a balanced mixture of organic fertilizers in lieu of expensive supplemental feeds.

The culture of flatfish in tidal-gate ponds in the British Isles is still in the developmental stages, although Shelbourne (1964) estimated that the entire harvest of North Sea plaice caught by the British fleet could be housed in shallow ponds about 200 hectares in surface area.

Whether this could be done profitably is another question. The same problems of oxygen renewal and waste removal would apply. Nash (1970a) reports that experimental tidal-gate ponds about 2 hectares in surface area were not successful because of extensive predation and low water temperatures in winter.

Perhaps the largest diked tidal-gate pond in the North American continent is in northern Puget Sound on the Lummi Indian reservation. Slightly over 300 hectares in surface area, this pond is intended for fish and shellfish production. However, the productivity of this development will not be known for some time as it was not completed until late 1971.

The use of tidal-gate ponds for marine fish culture in the northern latitudes of the North American continent will probably be limited to (1) short growing seasons to avoid low water temperatures in winter and (2) low production volumes to avoid excessive buildups of excreta and waste food.

Barriered Enclosures

In certain areas, such as parts of Japan and the Scandinavian Peninsula, the configuration of islands and inlets allows the formation of a large enclosure by placing barrier nets or screens across the entrance. Occasionally, narrow channels provide a site that can be screened at both ends. The Japanese do not seem to hesitate to use barrier nets several hundred meters or more long, and at least one barrier in a small Norwegian fjord is a formidable structure of concrete, steel, and complex screening.

However, most of these barriers are of relatively large mesh size to allow adequate water exchange and prevent structural stress. Therefore, they are used primarily as "growing-out" areas and only rarely as nursery areas for small fish.

There are disadvantages to this system. It is difficult to prevent the entry of predators and competitors; harvesting is difficult; and it is almost impossible to maintain stock inventories, which form the basis for determining the feeding levels. Indeed, there are very little accurate data on such systems. Nevertheless, under ideal conditions, certain types of barrier enclosures could have a high ratio of return for a small capital investment.

Raceways and Pumped Water

Raceway culture by gravity flow and pumped water has been successfully used for many years in the freshwater culture of salmon and trout. Tables, nomographs, etc., relating the rate of flow, raceway volume, water temperature, dissolved oxygen, and optimum ration of food for the production of salmon and trout are readily available and judiciously used by fish culturists. Pumped water, in any situation, requires (1) equipment; (2) power; and (3) maintenance. In the culture of marine fishes, pumped water is used in its simplest form in Norway where Atlantic salmon (Salmo salar) and rainbow trout are grown in barriered fjords. In certain locations, the natural water circulation is so poor that pumps are used to circulate the water and prevent harmful BOD buildups and oxygen depletion.

A more complex form of pumped water is the partially recycled system. When strategically placed, both fresh and salt water, under temperature control, can be used to stage anadromous salmon and trout through their adaptive cycles into full sea water. Most of the data used in the freshwater raceway culture of salmon and trout can be directly applied to marine raceway culture. Perhaps the largest and most complex installation of this type was built several years ago on the eastern shore of Nova Scotia, Canada, entirely for the commercial production of trout and salmon.

The culture of fish in waste water from the condenser coolant of nuclear-fueled thermal electric plants has been widely discussed, especially in the north temperate and subarctic regions where the heated water would presumably increase the growth of the fish. Scientists of the Whitefish Authority have been conducting successful experiments at the Hunterston, Scotland, nuclear plant for a number of years. Here, plaice

(Pleuronectes platessa) and sole (Solea solea) have been successfully reared in large numbers to a market size of 23 to 25 cm in 24 months in a raceway-type culture, entirely in the discharge cooling water of the power plant. Both plaice and sole survived concentrations of 0.002 to 0.1 ppm (chlorine) antifoulant, which is added continuously to the condenser cooling water. Nash (1970b) estimated that if only 10% of the flow from the Hunterston plant were used for culturing sole, over 1,300 metric tons of fish could be produced annually. A typical nuclear-fueled thermal electric power station built at a marine site in the United States will have a minimum generating capacity of 1,000 megawatts-electric (MWe). If the plant is designed to use marine water in a single pass to cool the condenser tubes, a station of this size will use 1,680-2,520 m^3 of pumped sea water per minute, with a thermal rise of 2 to 5°C. An average flow is approximately 2,100 m^3/min. Reasonable production estimates from these flows can be made by substituting present raceway production figures. Trout can be produced in a typical raceway culture system in fresh water at a minimum rate of 1,965 kilograms (kg) per kiloliter (kl) of flow per minute (min) and under ideal conditions at rates in excess of 5,900 kg/kl/min.

Figure 1 shows the theoretical annual production of salmon and trout that could be attained from a raceway culture system utilizing the full flow of the coolant discharge from 1,000 MWe marine power station. Note that a minimum stocking density of 2,000 kg/kl/min could annually produce over 3,000 metric tons of fish. What is needed now is an operational pilot farm, designed as an integral part of a marine thermal power station.

In a previous paper (Novotny, 1969), I presented a design for a pilot farm integrated with a 1,000 MWe marine power station, with approximately 6.5 hectares of moving water surface area (Figure 2). The pilot farm was designed to produce both fish and shellfish but had a planned annual yield of 3,000 metric tons of fish alone. However, no amount of scientific conjecture can replace the operational and biological experience that would be developed in managing a farm of this magnitude and until a pilot farm is constructed, any data will be speculative.

Floating Net-pens

When the Japanese began intensively culturing yellowtail in saltwater ponds, they encountered some typical problems of any intensive culture system. Crowded conditions and high rates of feeding increased the rate of oxygen depletion and caused rapid buildups of hydrogen sulfide, BOD, and bacterial-supporting fecal material. The end results were reductions in growth, food conversions, and survival of fish. Consequently, the number of new ponds has declined.

There has been a gradual shift from saltwater ponds to floating net-pens in the past 10 years. When floating pens are moored in areas of good water circulation, most of the environmental problems encountered in pond culture are reduced. Harada (1970) states that the majority of cultivated marine fishes are now grown in floating net-pens, although no data are given. Furukawa (1971) has evaluated the 1968 production of yellowtail for all three methods of culture: (1) embanked ponds; (2) net-enclosured ponds or bays; and (3) floating net-pens. A total of 327.6 hectares of surface area was involved, of which 48.2 ha were in diked ponds; 186.8 ha in barriered enclosures; and 92.6 ha in floating net-pens. The total yield of cultured yellowtails in

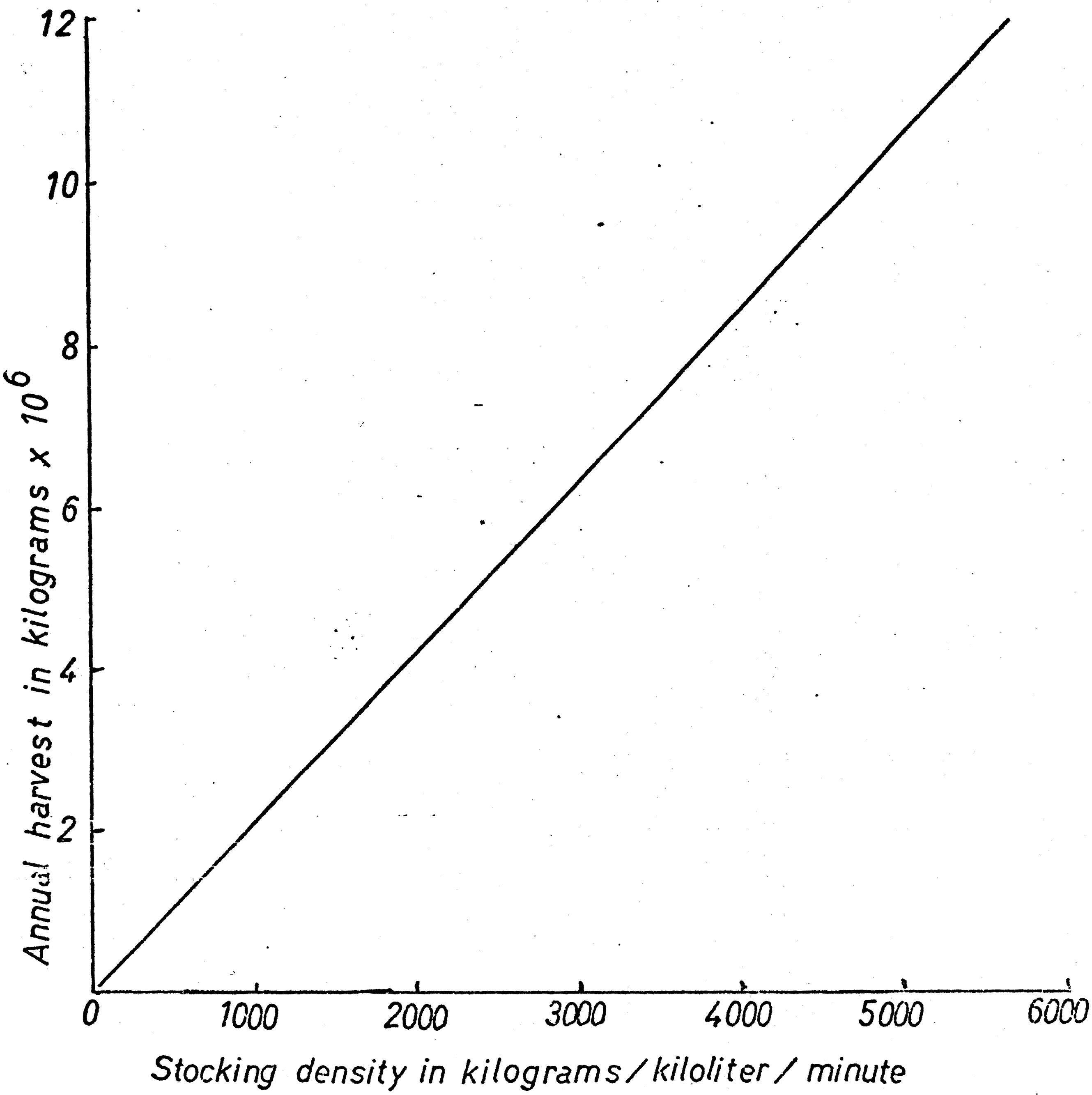

Figure 1. Possible annual yields of salmonid type fishes in raceway culture utilizing heated effluents. The flow is based on a probable condenser coolant discharge of 2100 m^3/minute from a typical 1000 MWe nuclearfueled thermal electric plant. Present U.S. trout stocking densities in raceways is 2000 to 6000 kg/kl/minute.

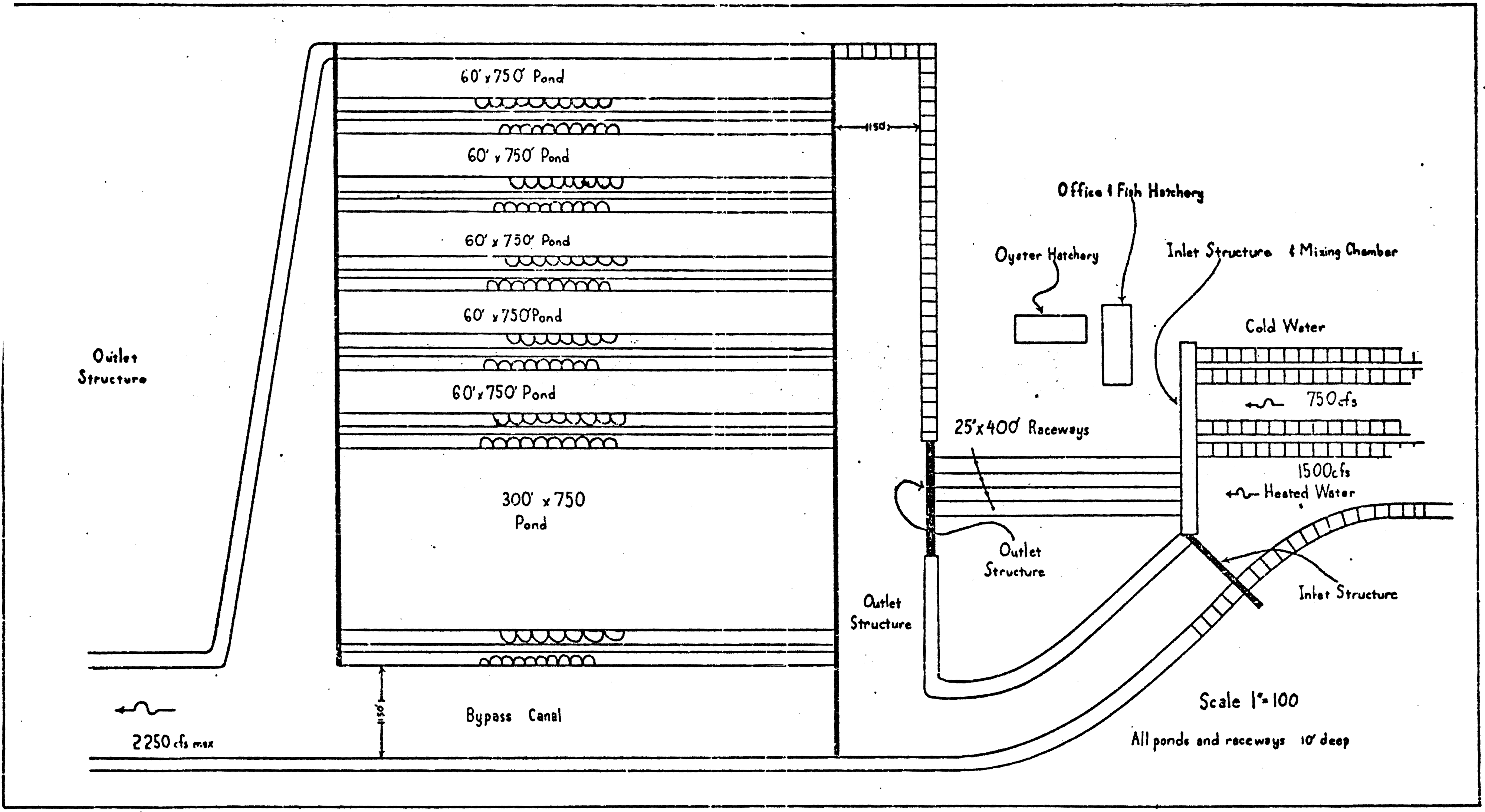

Figure 2. Maricultural pilot plant facility using heated effluent from a power plant.

1968 was 27,594 metric tons (MT) or an average 84.2 MT/ha. The 1961 harvest (from a lesser number of farms) was 2,344.5 MT. This is almost a 12-fold increase in production of yellowtail in 8 years. Unfortunately, Furukawa does not give production figures for the different methods of culture. The highest production by all methods was along the middle Pacific coast; this region yielded 376 MT/ha. The lowest was in the West Japan Sea--14 MT/ha.

Furukawa analyzed the economics of each method and ranked the expenditures on a percentage basis. The percentage of expenses for facilities, wear and tear, cost of business, miscellaneous items, and young fish (presumably because of reduced mortality) was less for floating pen culture than the other methods. The percentage of labor cost for floating pen culture was slightly higher, and the percentage of food cost was over 10% higher than for other methods, comprising 60% of the total expenditures. Thus, by the reduction of the other costs, food becomes the dominant item in pen culture. Any reduction in the cost of food, either directly or through increased conversion efficiency by fish then becomes significant.

PEN CULTURE OF PACIFIC SALMON IN PUGET SOUND

Early Efforts

In the summer of 1969, we began to conduct research in the culture of fishes in the marine waters of Puget Sound. We felt that the simplest and most economical means of culture would be in floating pens. We also felt that it would be necessary to select a fish that could reach marketable size in 12 to 18 months in order to be profitable.

Pacific salmon were selected because they are native to the region, readily available, and command a high price. The annual range of water temperature (6°C to 16°C) at our research station near Manchester is ideal for growing Pacific salmon, and the area is sheltered and unpolluted. The 4- to 5-meter range in tide, a water depth of 10 to 50 meters, and surface currents that reach a velocity of 0.5 m/second provide excellent water exchange. Also, the apparent successes of rearing saltwater adapted rainbow trout in rigid floating pens in Great Britain lent some credence to this initial premise.

Experiments were begun in the summer of 1969 with yearling coho salmon in rigid cages constructed of wood and hard plastic mesh. The fish were fed a formulated Oregon Moist Pellet (OMP) diet. Experiments were conducted at different levels of feeding (ration). We found that the coho salmon grew from 2.2 to 3.3% in body weight per day during the warmer periods at conversions of 1.4: 1 to 3.6: 1 but that the growth rates dropped to 0.2-0.4% in body weight per day during the coldest periods (Mahnken, Novotny, and Joiner [sic], 1970). Within 12 months, the fish had grown from 20 g to 500 g, with a high survival, indicating that we had a fish of good potential for purposes of mariculture.

The rigic plastic mesh, however, was relatively expensive and became brittle in sea water. The rigid frames were also expensive and too heavy and cumbersome to handle.

Within a matter of months, we developed a system of perimeter floats, constructed of treated wood and buoyed with styrofoam logs. Knotless nylon net pens of varying sizes were hung from the perimeter floats. Small, experimental pens, or "nursery" pens, were weighted by inserting PVC pipe frames filled with beach sand; larger "growing" or brood stock holding pens were weighted with chain along the net's rib lines at the bottom of the pen. This enabled us to easily manipulate the pens for sorting and weighing of fish and to change pens without stressing the fish. The knotless nylon is extremely durable, lasting at least 3 years with a minimum of maintenance. We now have nylon net pens ranging in volume from 2.7 m^3 nursery and experimental pens to 1,700 m^3 production pens (Novotny and Mahnken, 1972). The perimeter floats are moored to dock pilings or firmly anchored in open water to large rafts.

Secure moorings are essential, as large volumes of water move through the pens on each tidal cycle. A large pen with 100 m^2 of vertical netting below the water will have an approximate flow of 30 m^3 moving through the pen when the current velocity is 0.5 m/sec (Figure 3). The force of the water against the net pen is considerable as the orifice efficiency is only 50-60% when the net is slightly fouled with marine growth.

Adaptation of Juvenile Fish to Salt Water

Chum (*O. keta*) and pink salmon (*O. gorbuscha*) are the only two species of Pacific salmon capable of moving directly into sea water upon absorption of the yolk sac. Coho, chinook, and sockeye (*O. nerka*) salmon require additional residence in fresh water until they are "smolted." Smolting is a condition in juvenile salmon generally associated with a combination of size and accelerating photoperiod.

Although it is desirable to acclimate Pacific salmon to sea water gradually (this appears to be a common practice in Japan) and at times it has the added advantage of allowing entry at a smaller size (Kepshire

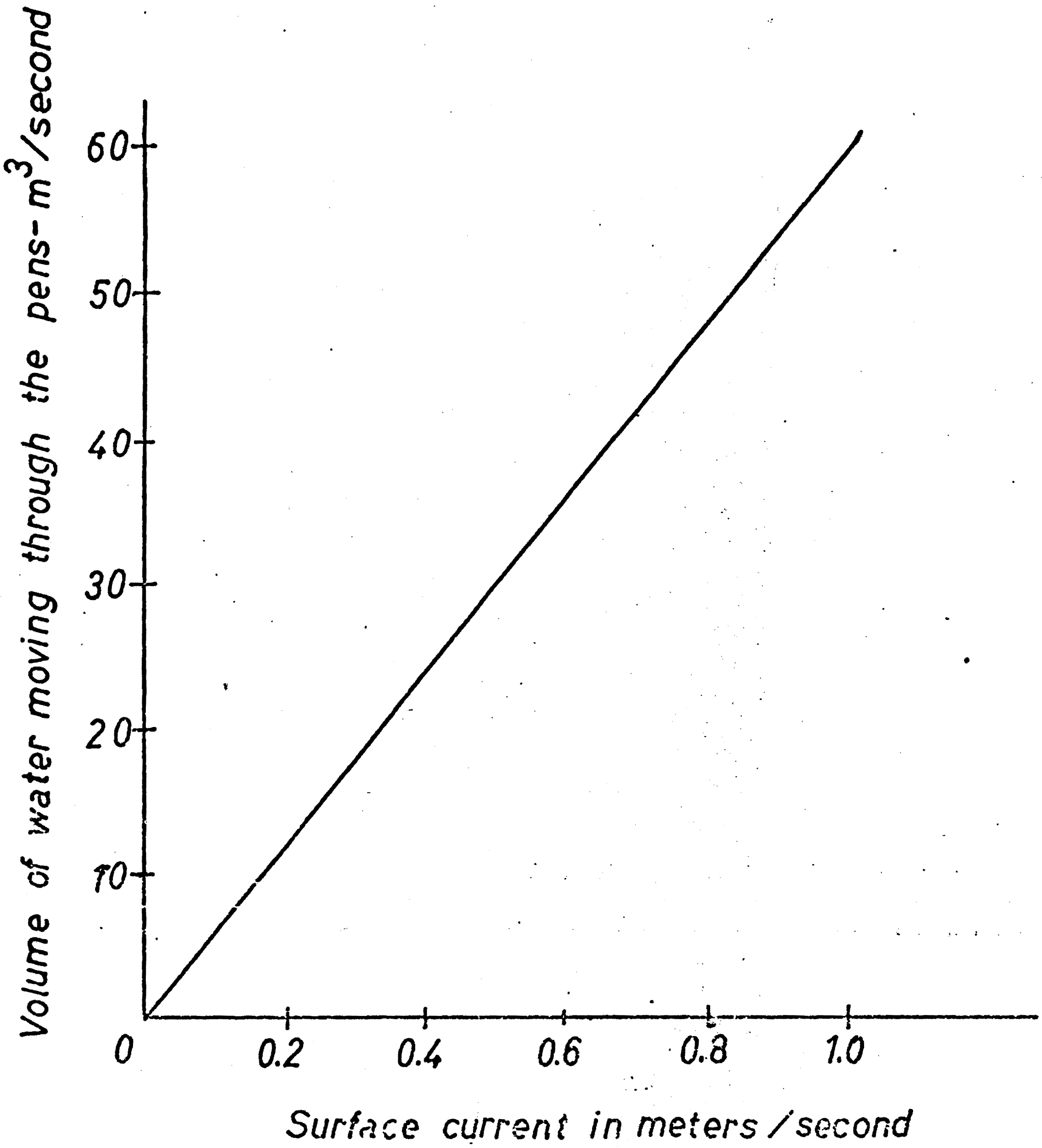

Figure 3. Volumes of water moving through a practical production pen in relation to tidal flow. Square pen, 15 m x 15 m x 7 m deep, and approximately 60% orifice efficiency.

and McNeil, 1972), gradual acclimatization presents a difficult logistics problem when working with hundreds of thousands of fish.

We found that healthy yearling coho salmon (age 1 fish) can be moved directly into sea water in late winter or early spring at a minimum size of 12 to 15 g and preferably 18 to 20 g. Fall chinook salmon can be moved directly into salt water in their first spring of life (age 0 fish) at 5 g and preferably 8 g (Novotny and Mahnken, 1971a).

In the early growth stages in fresh water, fall chinook salmon grow at an accelerating rate as the water temperatures rise rapidly in the spring. This growth can be repressed by forced entry into Puget Sound salt water, which rises in temperature at a slower rate. Fish started at 2 g in April did not grow as rapidly in salt water as another stock held in fresh water until June; fish introduced early into salt water never did attain the weight of those introduced later (Figure 4). Survival of the early entrant is also poor. The overall effects of premature saltwater entry on growth are still visible 1-1/2 years later (Figure 5). The premature entrants were smaller and the ratio of weight to length was smaller.

Similar effects can be seen with yearling coho. Figure 6 presents the length-weight relation of coho salmon that were placed in the pens as April yearlings with an average weight of 10.5 g. Their freshwater growth was held back by low water temperatures. Figure 7 shows the length-weight relations of coho salmon that were placed in the pens in January as 20 g subyearlings. Most fish of each stock matured as 3-year-olds at approximately the same time of year.

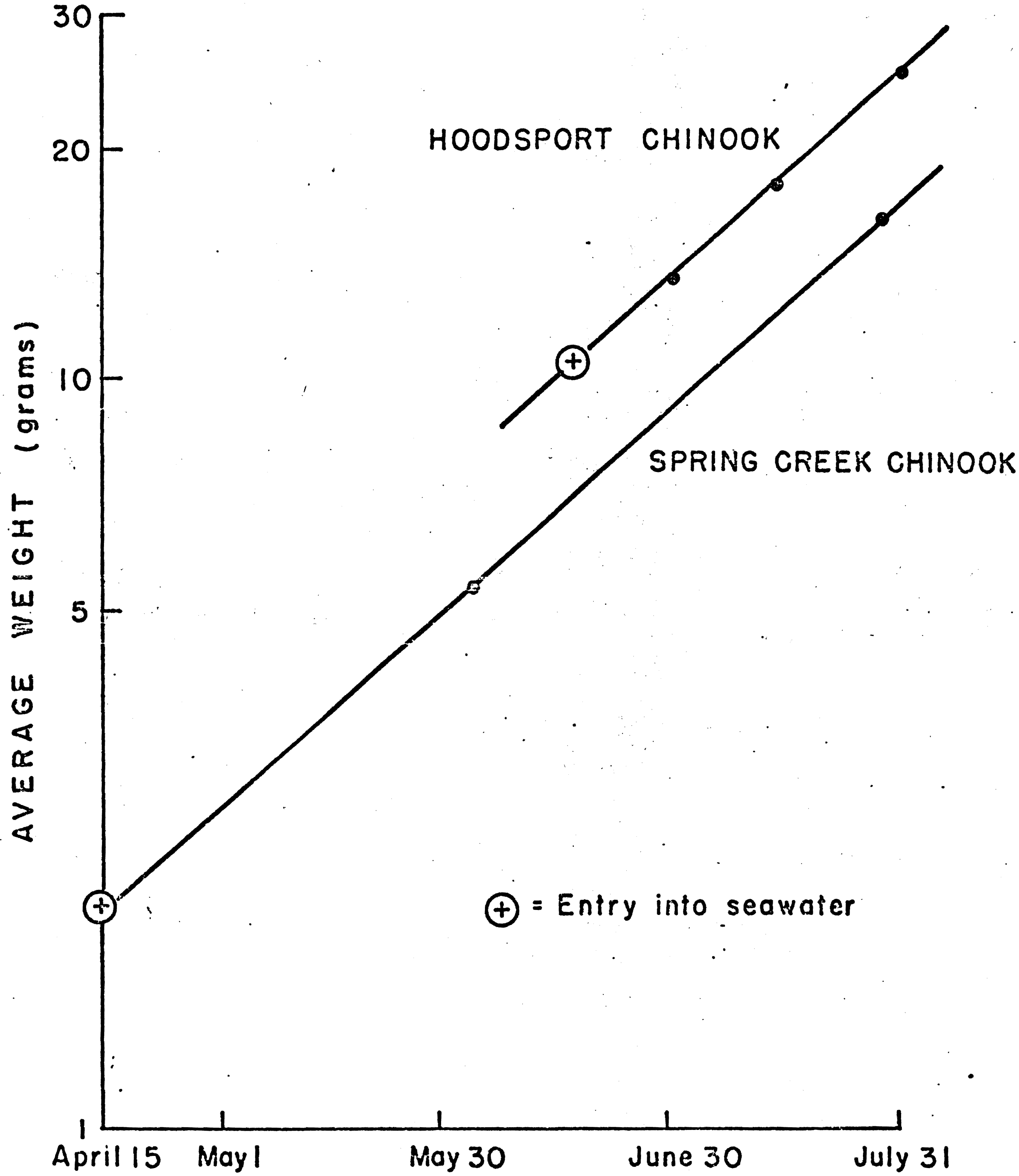

Figure 4. A comparison of early saltwater growth of fall chinook salmon started at different sizes.

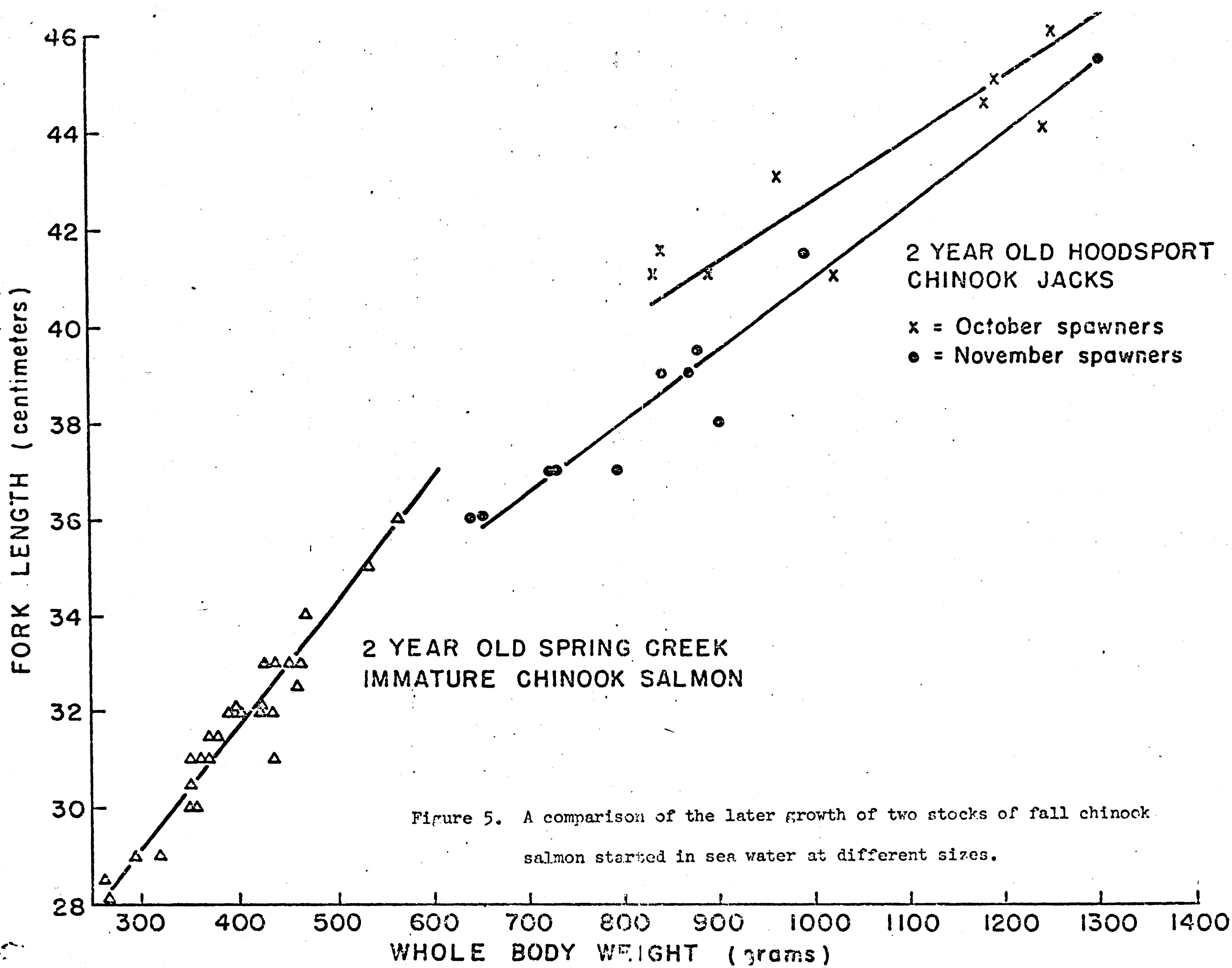

Figure 5. A comparison of the later growth of two stocks of fall chinook salmon started in sea water at different sizes.

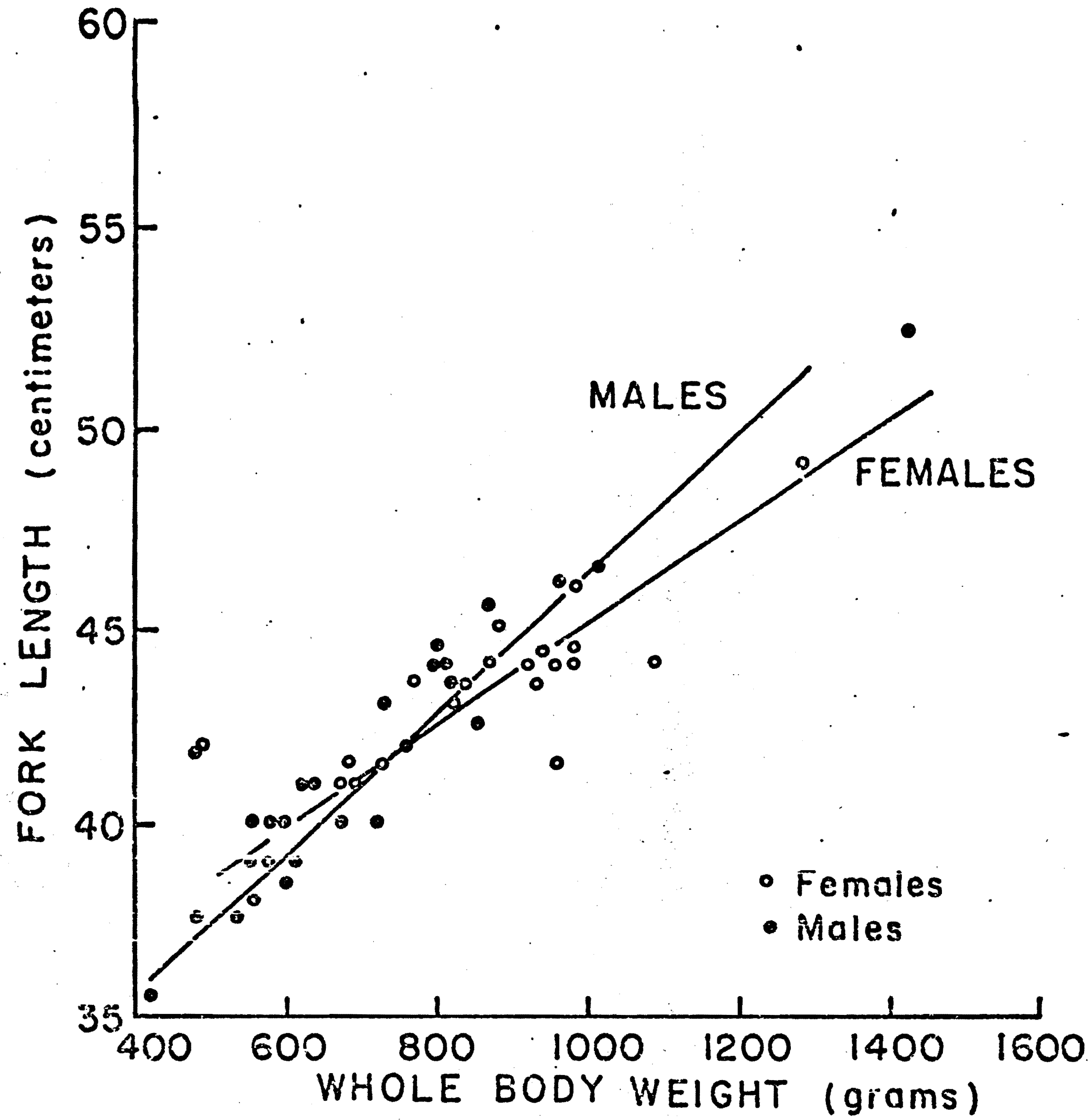

Figure 6. A comparison of the length-weight relations of mature 3-year-old male and female coho salmon (Eagle Creek stock).

Rapid Early Growth

Rapid growth is essential in pen culture as any increase in rearing time increases the overall cost per unit of fish and the risk factor (losses from escape or mortality). Coho salmon released from Puget Sound hatcheries normally reach maturity 36 months from fertilization. At this time they will weigh from 3 to 7 kg. At 24 months after fertilization, the size of Puget Sound coho will rarely exceed 1 kg; in fact, the greatest growth increments of this species (in the wild) occur in the last 4 to 6 months of its life cycle.

When we compare the early growth of Pacific salmon with some of the tropical and subtropical fish species, the salmon does not appear to be a particularly appropriate species for marine culture. Figure 8 is a growth curve for cultured yellowtail. One is immediately impressed with the astonishing rate of growth in the first 2 to 3 months and the equally impressive weight of 3 kg at 18 months. Similarly, Figure 9 is a growth curve for wild dolphin (Coryphaena hippurus). This warmwater species reaches 4.5 kg when 18 months old and, although I could find no data for the very early growth stages, the slope of the curve indicates a rate of growth equal to or exceeding that of the cultured yellowtail. The growth rate of wild cobia, Rachycentron canadum (Figure 10), in subtropical waters equals or exceeds that of the cultured yellowtail in its first 18 months. The last of the rapid growing tropical and subtropical species that I examined was Thunnus albacares, the yellowfin tuna. In the wild, these fish will weigh slightly over 3 kg at the end of their first year (Figure 11).

All of the above tropical and subtropical species have two features in common that Pacific salmon do not have: (1) The eggs hatch in 3 to 10 days

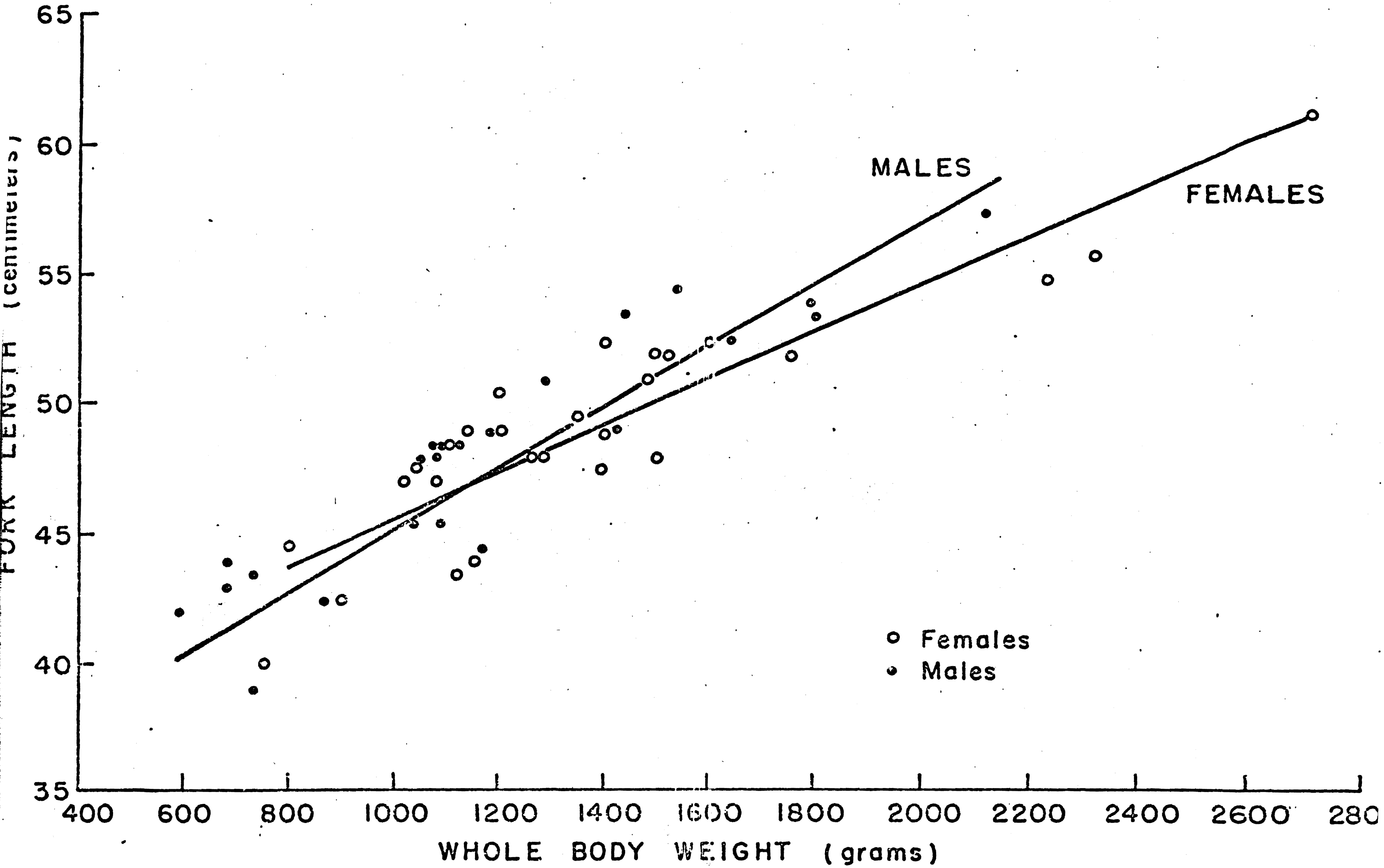

Figure 7. A comparison of the length-weight relations of mature 3-year-old male and female coho salmon (Leavenworth stock).

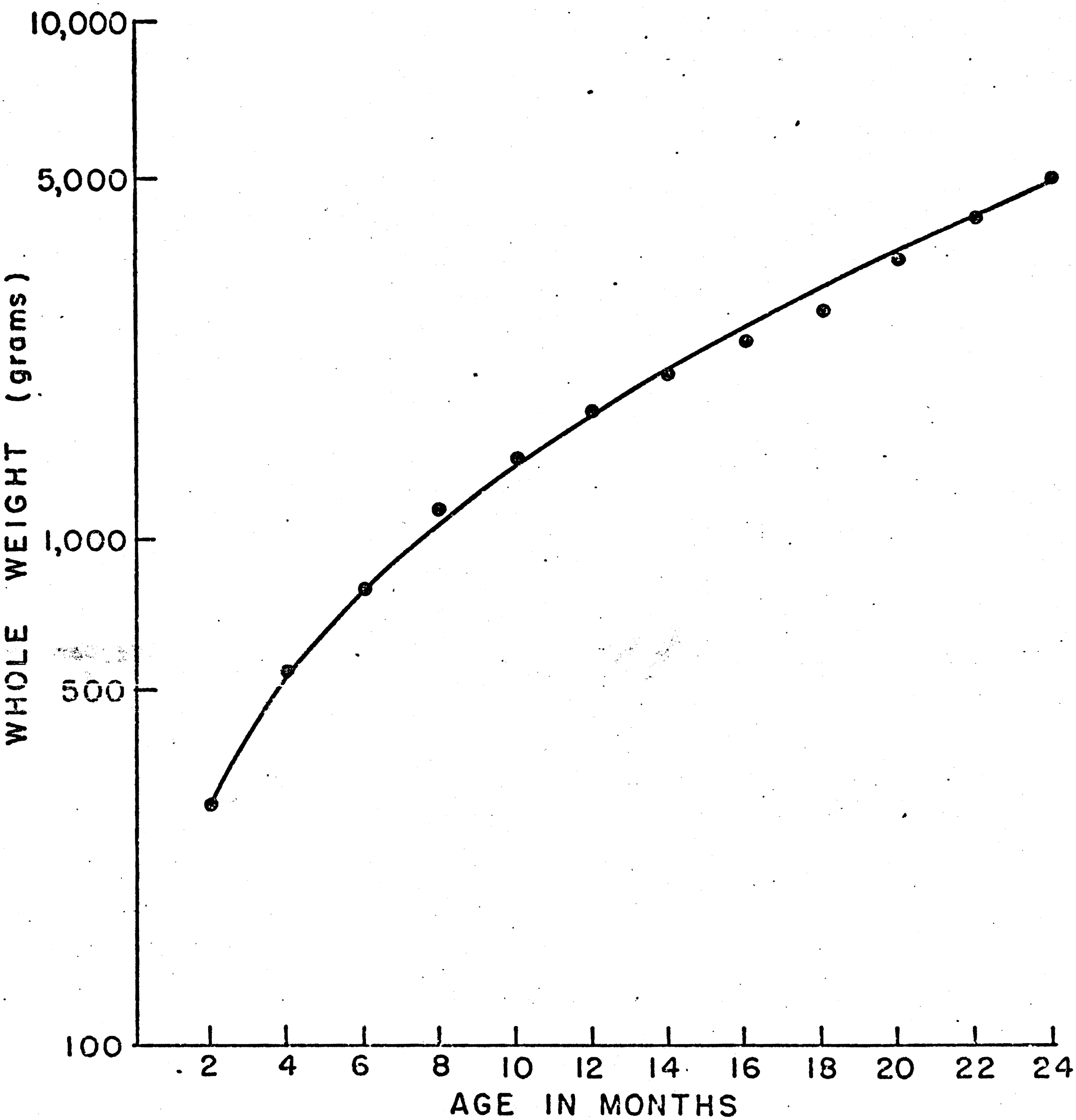

Figure 8. The growth of cultured yellowtail (*Seriola quinqueradiata*).
(From Harada, 1970.)

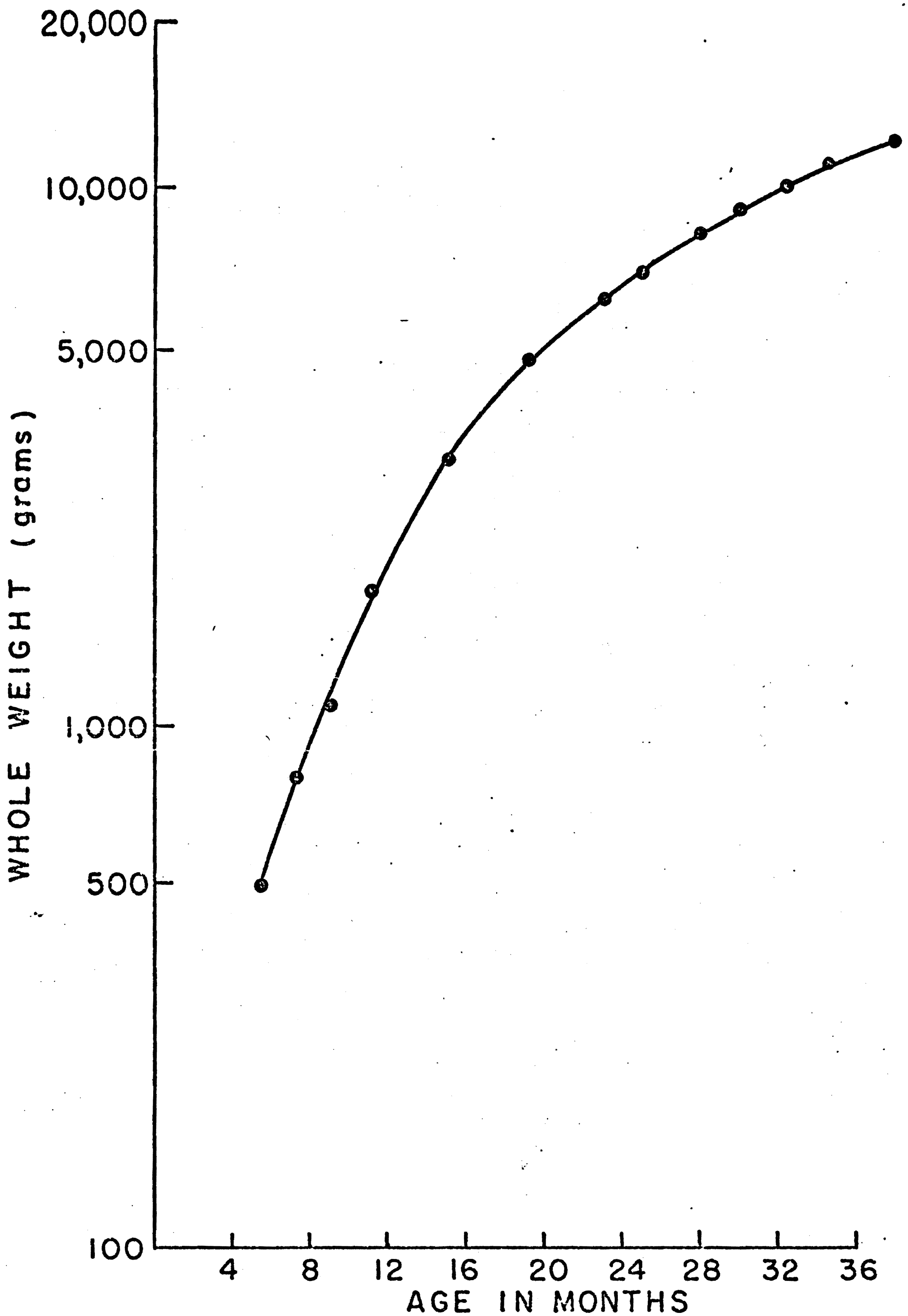

Figure 9. The growth of the dolphin (Coryphaena hippurus) in North Carolina waters. (From Rose and Hassler, 1968.)

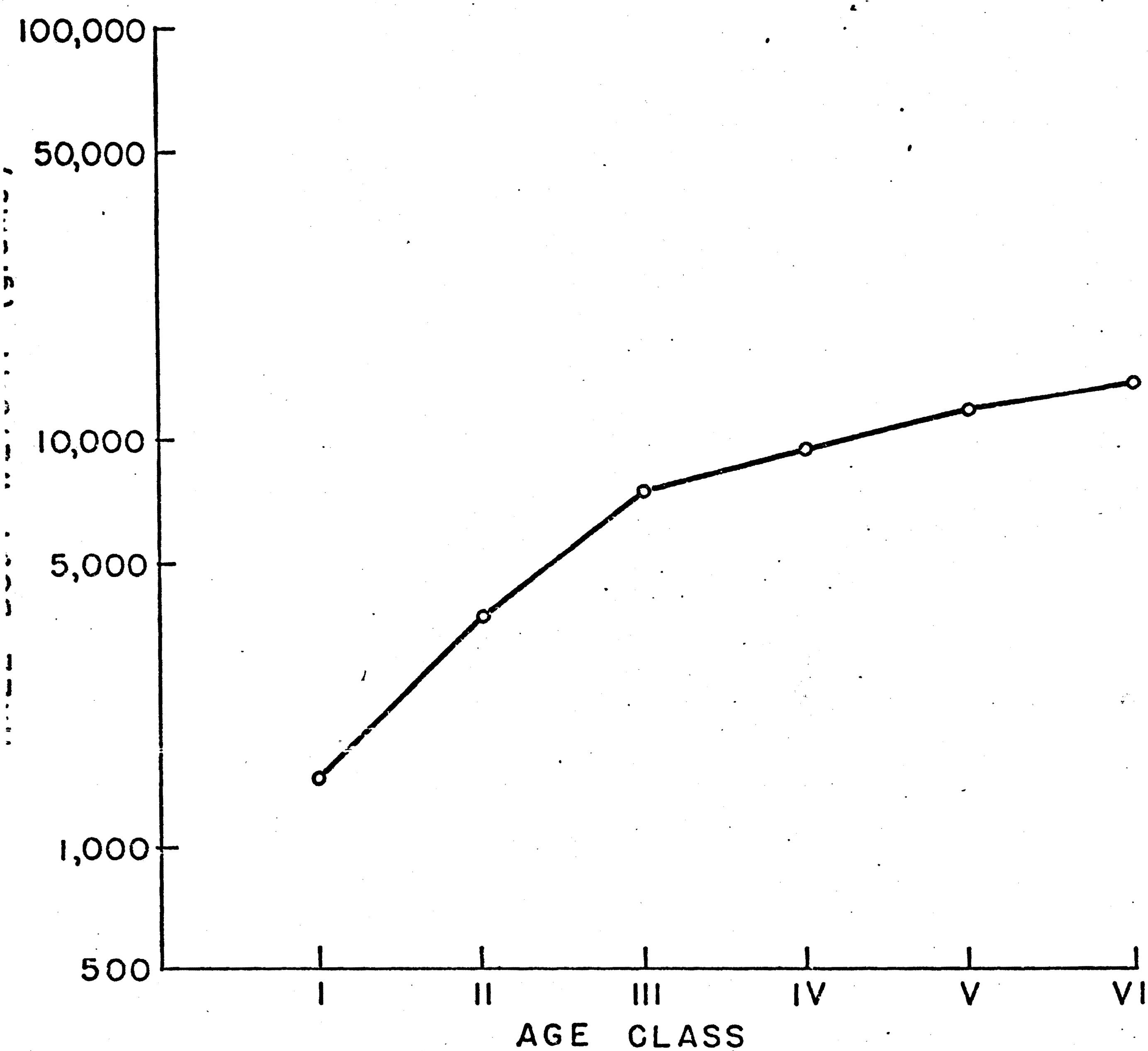

Figure 10. The growth of the cobia (*Rachycentron canadum*) compiled from the average weight of six age classes. (From Richards, 1967.)

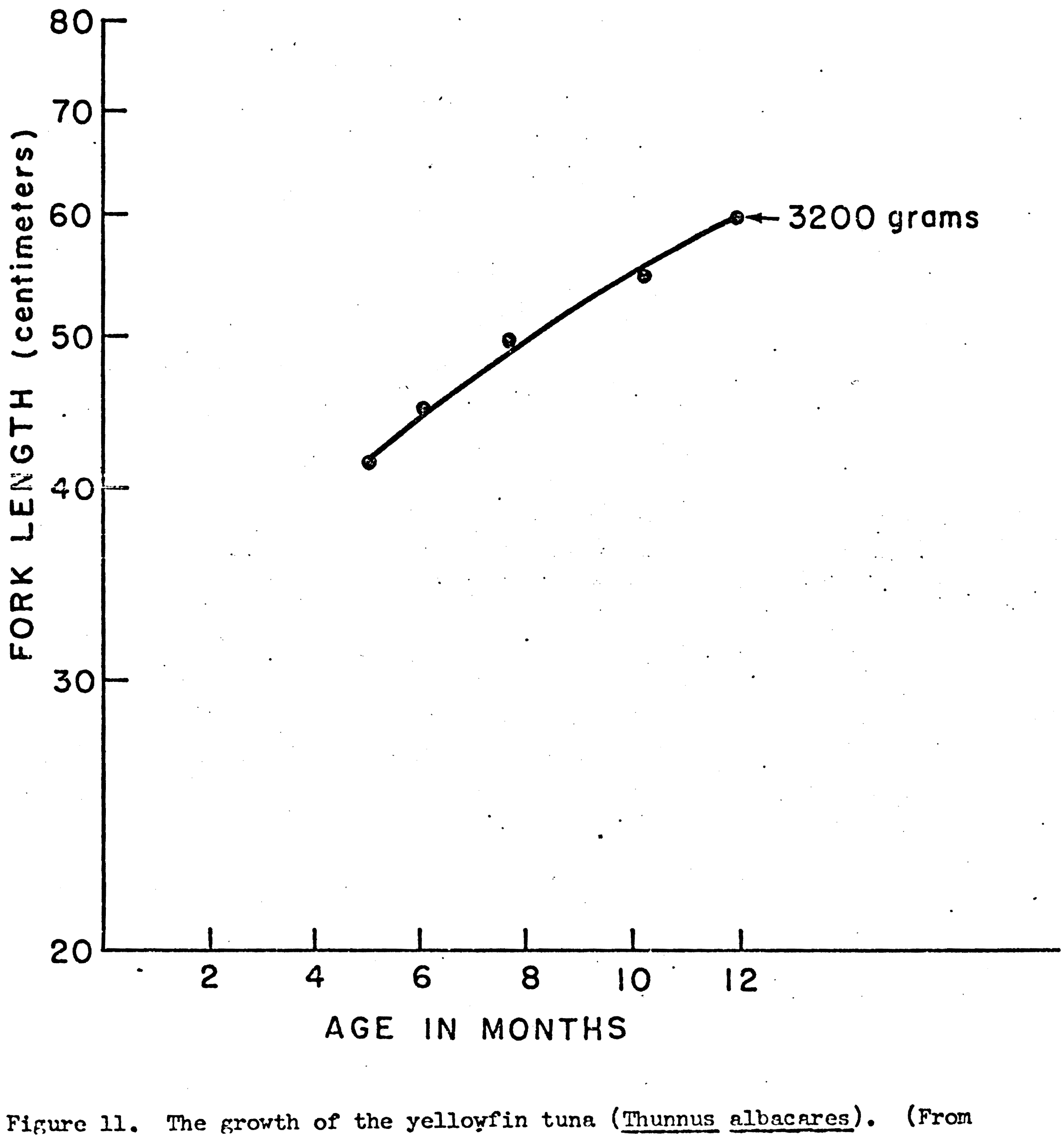

Figure 11. The growth of the yellowfin tuna (*Thunnus albacares*). (From Shirota, 1970.)

compared to 100-150 days for Pacific salmon and (2) The early fry have enormous mouths in proportion to their body sizes, thus enabling them to select larger food organisms at the commencement of feeding. Shirota (1970), in his studies of the mouth sizes of larval fishes, found that fishes such as the yellowtail and yellowfin tuna were actually smaller than clupeoid fishes at the time of yolk sac absorption but had larger mouths.

However, the attainment of this rapid growth, at least in the case of the yellowtail, is extracted at a large price: (1) poor food conversion (from 6:1 to 8:1) and (2) extreme difficulties in spawning the parent fish and obtaining healthy fry. Although the Japanese are expending major efforts in developing applied techniques to produce viable and healthy eggs and fry of yellowtail from captured and cultured parent stocks, the entire industry is still based on the capture of wild fry 1 to 2 cm long.

Pacific salmon, on the other hand, have been cultured for many years, and although the embryonic development is slow, survival of 90% of the population from fertilization of the egg through yolk sac absorption is the rule rather than the exception. In addition, the fry will commence feeding immediately on artificial diets and will convert food (in the early stages) at ratios of 2.5:1 to 3:1 or less.

In 1970 when the pilot salmon farm experiment was initiated, we reasoned that coho salmon could be accelerated in growth to a smolting size of 15-20 g within 6 months after hatching of the eggs and thus be prepared for saltwater entry a full 9 months ahead of normal hatchery schedules. We planned to do this by incubating the eggs and rearing the fry and fingerlings in 10 to 12°C water and by feeding the fish an efficient commercial dry diet based on the Abernathy formula. We were successful in maintaining our incubation temperatures but had difficulties in maintaining the desired pond temperatures. Cold weather in February almost negated the small amount of heat that was introduced into the ponds from a rather crude heating apparatus. Nevertheless, the growth of about 60% of the stock was accelerated in time for an early saltwater entry. The fish were graded and all over 18 g were introduced into the pens in the first week in July. The remaining fish did not reach the proper size and condition until mid-August. At this time, they too were put into saltwater pens.

Figure 12 is a summary of the time and growth relations of these two lots of fish. We expected excellent growth of the first lot of coho during the summer and fall, but we also expected less growth during the winter than actually occurred. Second, we expected that the average weight of the first lot would always exceed that of the second, but we did not expect that a large proportion of the late entries would revert to a presmolt condition. The growth curve shown for the fish that reverted to a presmolt condition is only approximate, as there was considerable variation in weight among the salmon. Nevertheless, in most of the fish, strong parr marks (a typical presmolt physical condition) reappeared, and there was little or no growth during the winter. Survival was relatively high and as the spring photoperiod increased, the fish attained the size and smolt conditions of normal hatchery yearlings. Otto (1971) reported a decrease in growth of presmolt coho subjected to higher salinities after August, and others have found strong correlations between photoperiod and smoltification.

Although we must document this experimentally, our general feeling is that the greater the time past the summer photoperiod peak (July) that coho salmon smolts of age group 0 are placed in salt water, the greater will

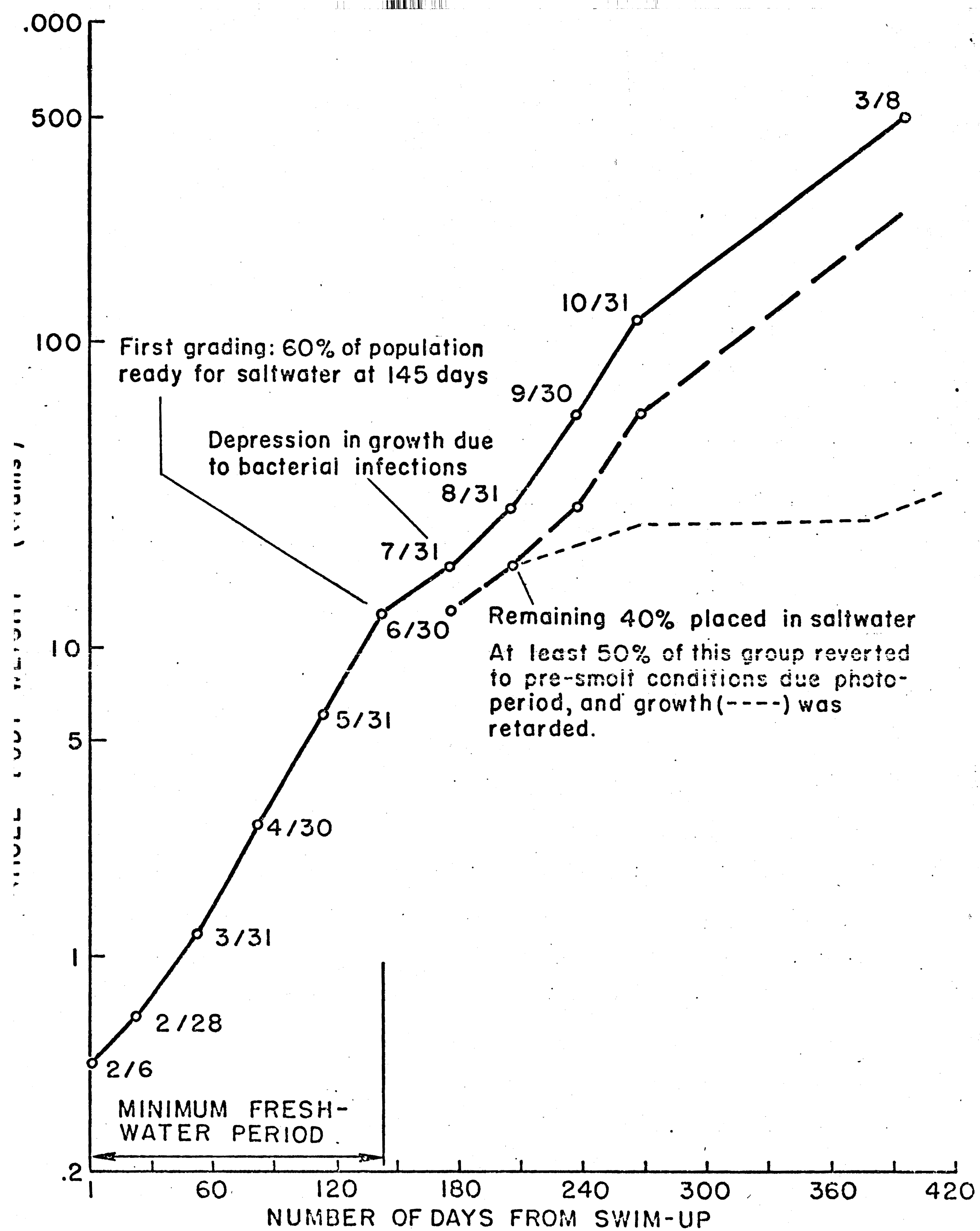

Figure 12. The growth and staging phases of zero-age coho salmon

(Oncorhynchus kisutch) in a large-scale pilot farm operation.

be the percentage of fish that will revert to a presmolt condition.

The harvest of the faster growing coho began in January, 1972, exactly 12 months from hatch at 350 g. Between January and March over 60,000 coho salmon were shipped to market, and over 6,000 were held for future brood stock simply because they were too big. These fish (at 18 months posthatch) now range from 0.7 to 2.5 kg. All of the coho in the pilot farm have been reared to market size or larger entirely on commercially available dry pellets. The overall food conversions were approximately 1.5:1.

Figure 13 is a first-year growth curve for cultured pompano (a highly valued subtropical species of marine fish). It appears evident that under the proper conditions the rate of growth of the coho salmon can approach or equal the growth rates of some warmwater marine species and with far less difficulties in culture.

Unfortunately, we have not been able to rear chinook salmon as successfully as we have reared coho on the available diets. Figure 14 is a series of growth curves for chinook salmon grown in two different years. There is a distinct reduction in growth in the winter, and the period of reduced growth is longer for chinook than for coho salmon. Figure 15 is a theoretical growth curve for the chinook salmon based on average water temperatures of Clam Bay. The first chinook salmon were not harvested (350 g) from the pilot farm until the last week in April (1972), and the last of the harvest was completed in late June. The food conversions of the chinook salmon are not particularly good (1.8:1 to 3:1). The chinook prefer the OMP diet (which is more expensive to purchase and store) over dry pellet diets and seem to be more susceptible to disease than the coho salmon. Approximately 100,000 chinook salmon were harvested from the pilot farm, and serious research

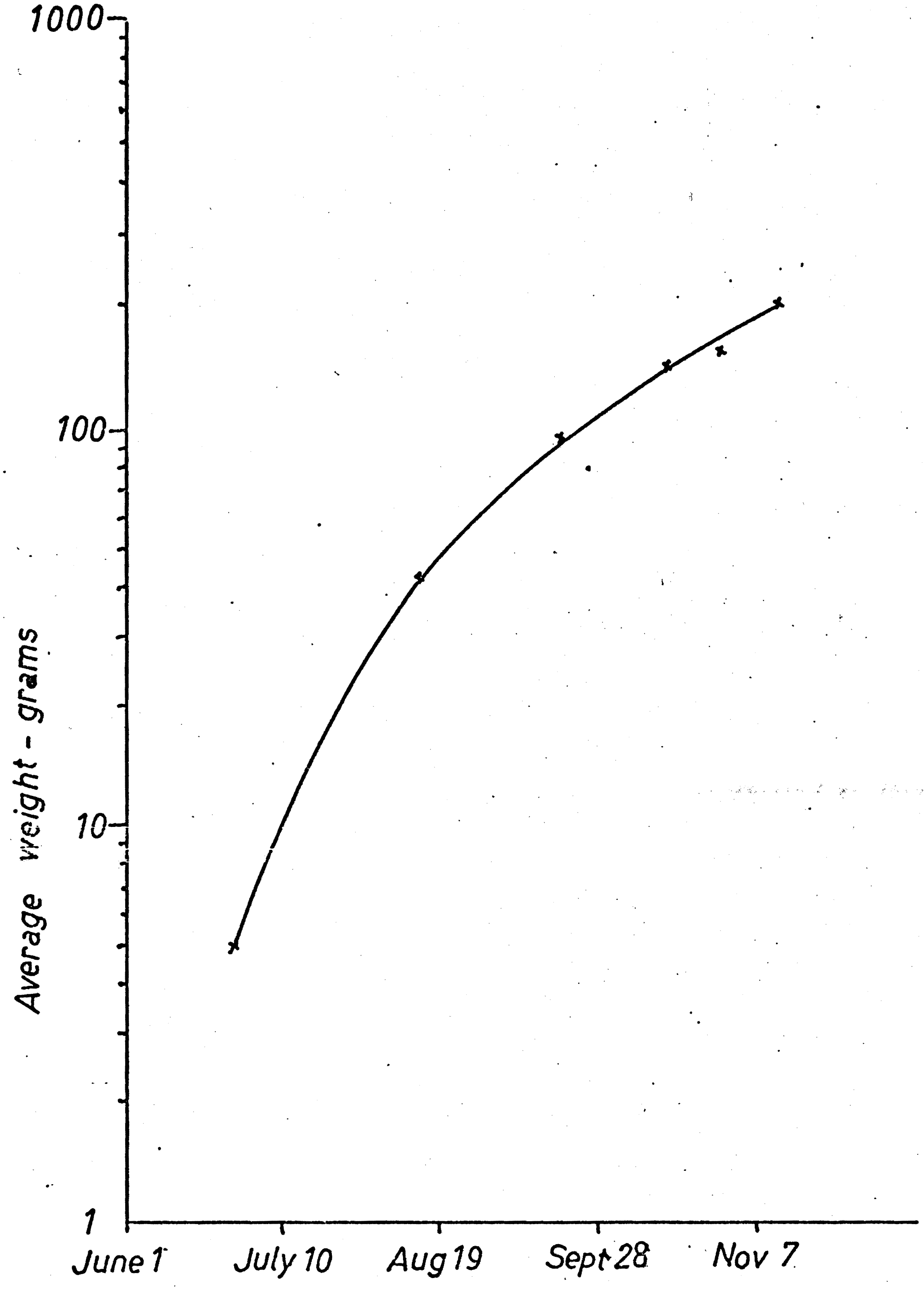

Figure 13. The growth of cultured Florida pompano (Trachinotus carolinus) during the first year in captivity. (From Iverson and Berry, 1968.)

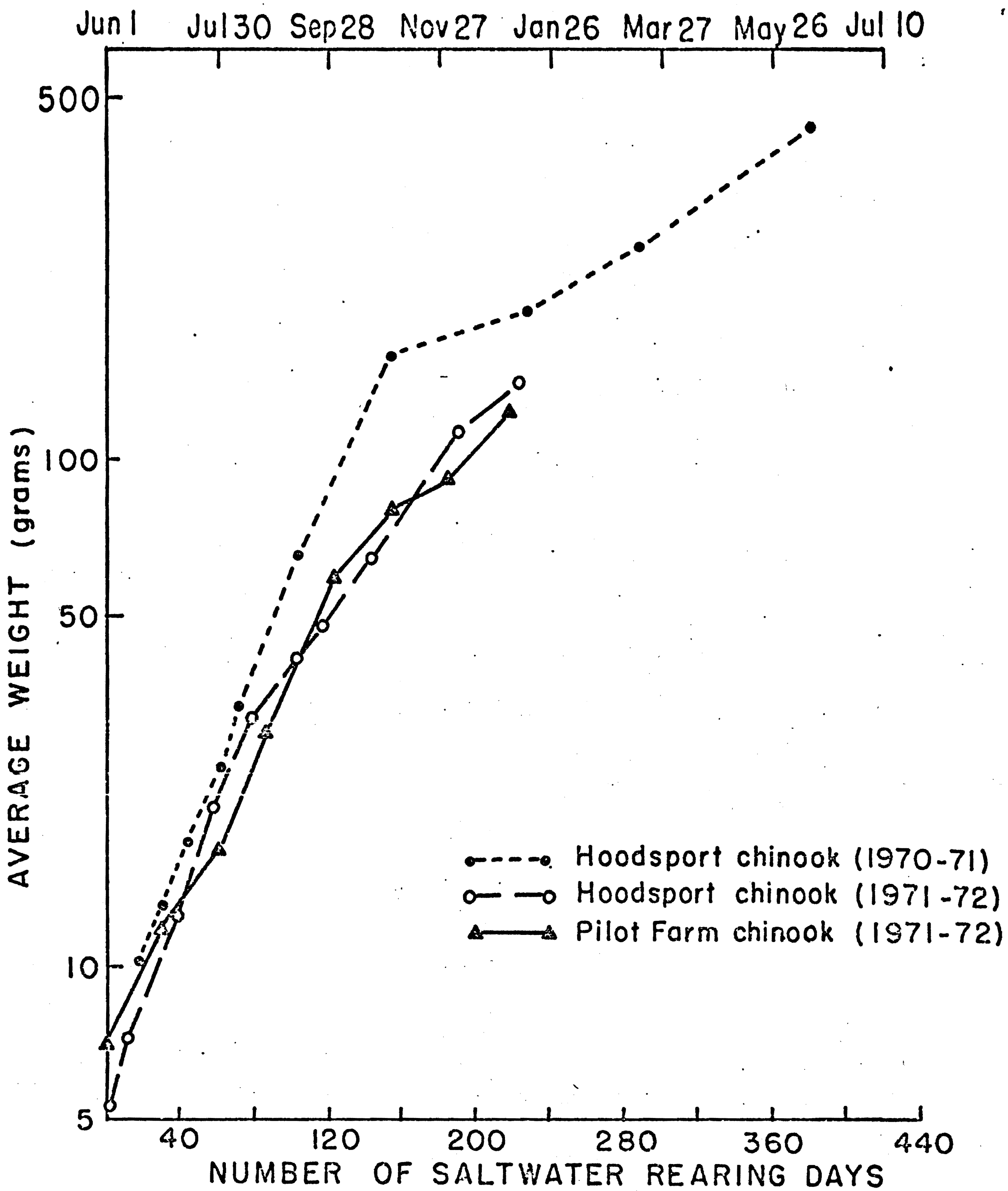

Figure 14. The growth of three lots of fall chinook salmon reared in pens in Clam Bay, Puget Sound. Note: water temperatures in 1970-71 were higher than in the following year.

efforts on this species will continue. However, at the present time, the coho salmon appears to be the most desirable species for commercial culture when viewed from the economic standpoint.

Stocking Density and Survival

It will be some months before a complete analysis of the pilot farm is prepared. However, other research on the marine culture of Pacific salmon is also being conducted, especially in regard to stocking density and survival. On the basis of our earlier research, we determined a safe density of 16 kg of fish per cubic meter of water in the pens. Between April and July, 1971, we reared yearling coho salmon for 77 days in a 22-cubic-meter pen with an initial stocking density of 8 kg/m^3 and a final density of 16 kg/m^3. Survival of fish during this growing period was 98%. The coho in the pilot farm pens were grown at a final density of about 28 kg/m^3. Final survival at this density is not now known, but it is believed to be extremely high. Finally, one lot of male pink x female chinook salmon hybrids were grown in 8 months to a final density of 38 kg/m^3 in a 2.7 m^3 pen with a known 70% survival.

A practical working depth for a commercial growing pen is about 7 meters. If we assume that Pacific salmon can be grown to final densities of from 16 to 25 kg/m^3 and harvested within 12 months from commencement of feeding, the annual production of fish per surface hectare will range from 1.12×10^6 to 1.75×10^6 kg/ha. If we assume that half of the surface area were covered with working rafts, etc., and not in actual production, the production efficiency for a body of water is still extremely high.

Diseases and Parasites

Surprisingly, we have had few problems with parasitism in our pen culture in Puget Sound. Occasionally, young fish are attacked by a predatory

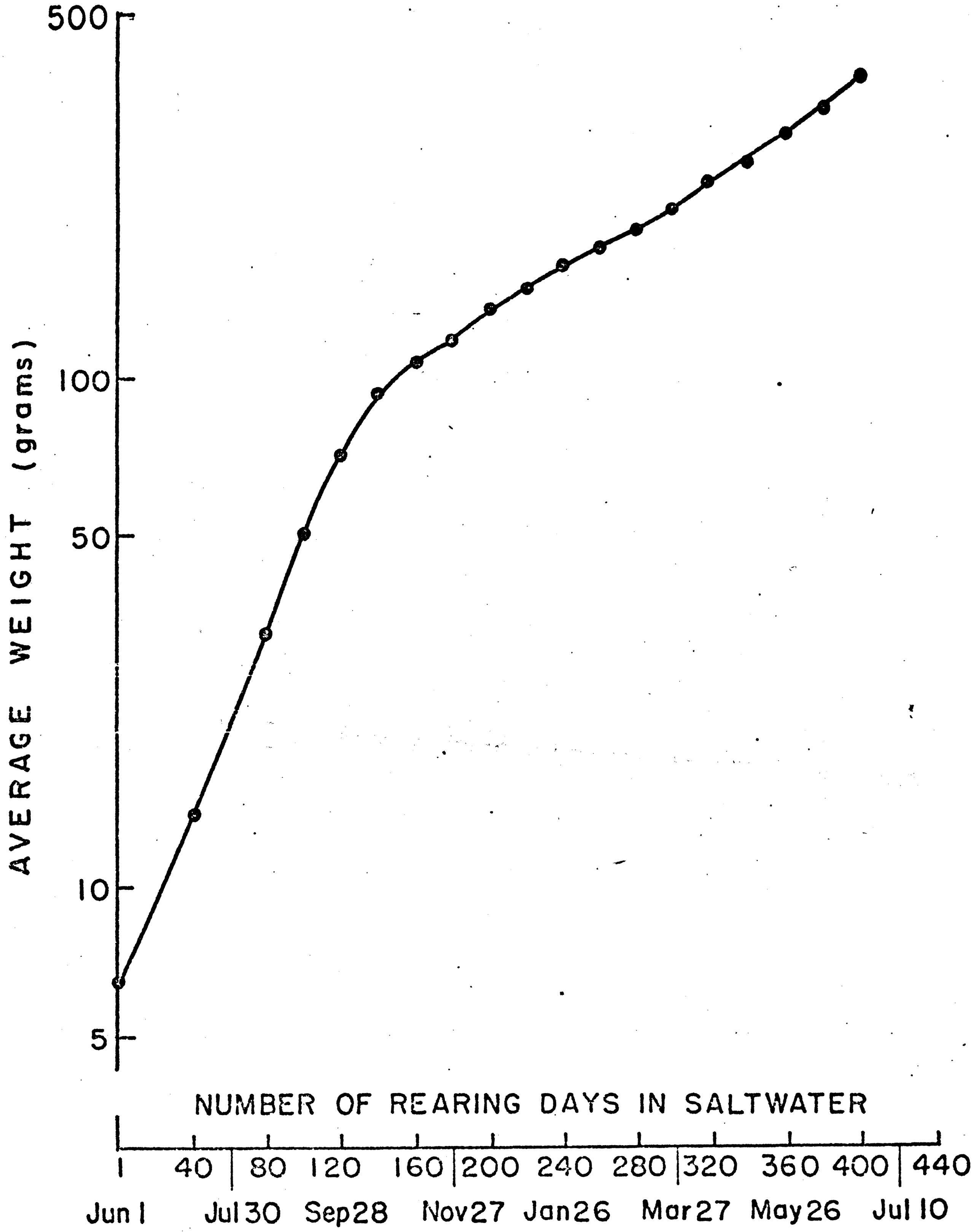

Figure 15. A theoretical growth curve for chinook salmon grown in Clam Bay, Puget Sound, on an OMP diet. Data based on average water temperatures.

isopod (Novotny and Mahnken, 1971b), and older fish may have a few parasitic copepods on their skin. Chinook salmon cultured in southern Puget Sound (Squaxin Island) in 1971 suffered from a fungus caused by an unidentified myxobacterial infection.

Our worst problems are caused by bacterial diseases of both fresh- and saltwater origin. If, on the basis of 3 years' experience, I were to rank the species of Pacific salmon in order of resistance to disease, response to controls, and survival in saltwater culture, the order would be (1) coho; (2) chinook; (3) sockeye; (4) pink; and last (5) chum salmon.

The major diseases that we have encountered are (1) furunculosis, Aeromonas salmonicida; (2) kidney disease, Cornybacterium sp. (both of freshwater origin); and (3) vibriosis (a marine bacterial infection) which in our region has been identified almost exclusively as Vibrio anguillarum. At least four and possibly five strains of V. anguillarum have been isolated from sick or moribund Pacific salmon cultured at Clam Bay.

Other scientists have also found vibrio in salmon. Evelyn (1971), for example, reported major outbreaks of V. anguillarum in four species of Pacific salmon during the summer.

We encountered vibriosis in the culture of five species of Pacific salmon and in all of the hybrids that we have worked with. In February, 1972, when the water temperature was 6.5°C, we isolated vibrios from moribund yearling pink salmon and yearling chinook x pink hybrids. We had never encountered vibriosis at such a low temperature before. The major outbreaks of vibriosis occur in late May or early June, mid-August, and late in September. The first outbreak is usually extremely virulent. I conducted tests on chinook salmon fingerlings reared at different water temperatures between May and

July of 1971 with no antibiotic treatments. Fish reared at ambient temperatures (10.0 to 12.8°C) suffered an average mortality of 19%; those at 10.0 to 13.0°C suffered a 29% mortality, and those fish reared at 10.8 to 15.0°C suffered a 28% average mortality. The lots reared at 11.8 to 17.0°C had a staggering 78% mortality. Virtually all of the fish died from vibriosis.

Fortunately, fish with vibrio respond well to antibiotic treatment. Veterinary grade terramycin (TM50D) is added to the diet at the processing plant before the food is made into pellets. Our standard practice calls for feeding these pellets to the fish for 5 days at therapeutic levels, followed by 3 to 5 days at prophylactic levels. The response in coho, chinook, and sockeye salmon is dramatic and rapid but much less so in pink and chum salmon. An examination, under an ultraviolet microscope, of the rib bones of coho salmon harvested from the pilot farm revealed two distinct tetracycline marks. The distinct bands were the result of the deposition in the bones of tetracycline from the oral administration of TM50D in August and late September.

We generally conduct antibiotic sensitivity tests on isolated cultures. The sensitivities vary with the strain of vibrios and the season, but in general we found that the sulfa drugs are useless, the sensitivity to terramycin is good, and the most consistently sensitive antibiotic tested thus far is furoxone. We hope to try this drug experimentally on pink salmon this year.

Furunculosis is carried dominantly by pink and chum salmon from fresh water. The first outbreaks occur in June and are transmitted in salt water in the pens to epidemic proportions. Terramycin treatment is effective in

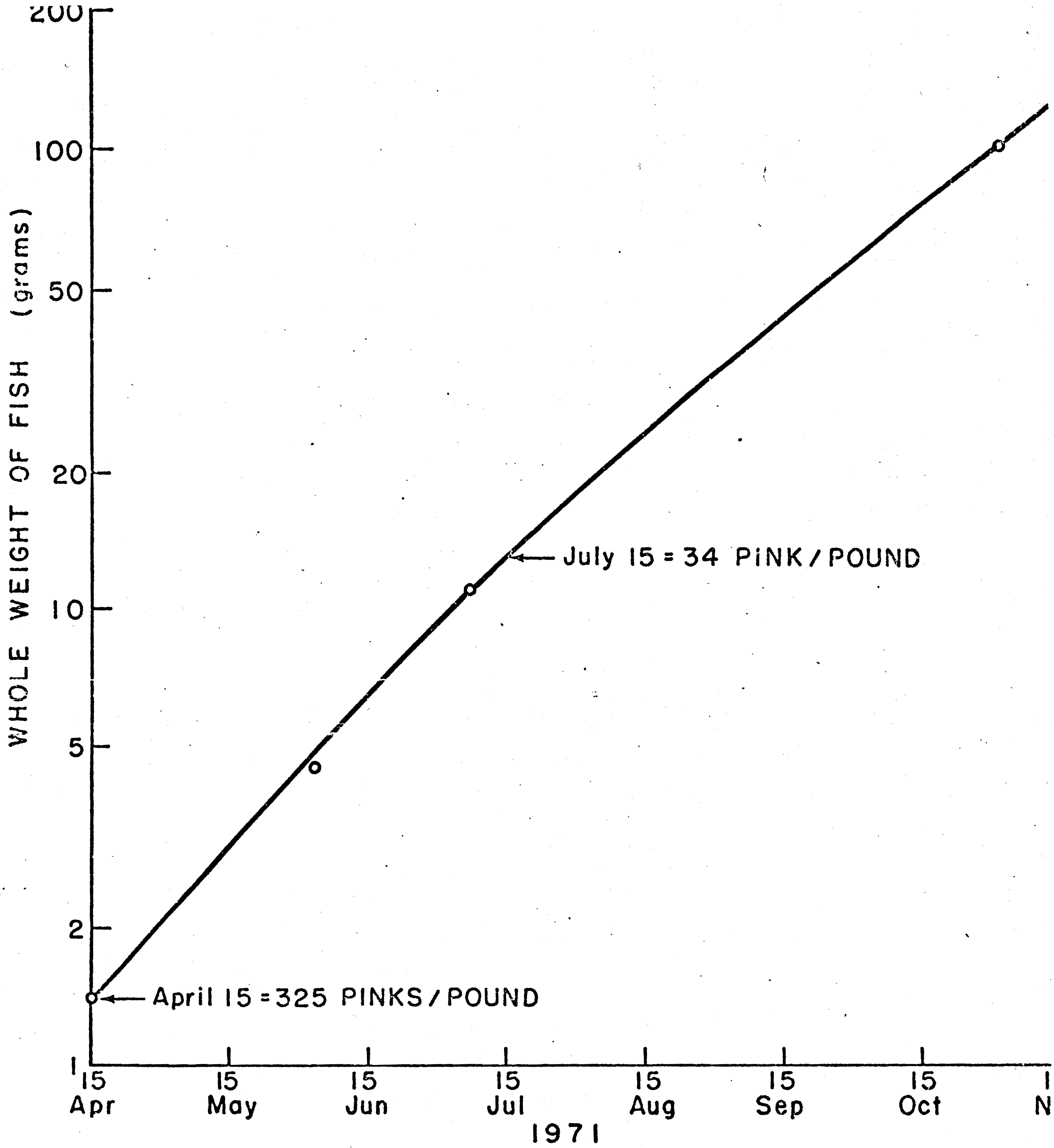

Figure 16. The growth of Alaska pink salmon reared at Clam Bay, Puget Sound.

pink salmon but much less so in chum salmon. However, when the fish are not fed their antibiotic diet for a few days, the mortalities rise rapidly. This condition continues throughout the summer and into the fall.

Figure 16 shows a growth curve for pen cultured pink salmon. The weights, however, are probably less than one might obtain under more desirable conditions; some of the fish were sick and affected the data. This is perhaps more comprehensible when one examines the survival curve for the same lot of fish (Figure 17). The situation is almost identical with chum salmon. Both species are being raised on the OMP diet.

The chinook salmon is much more resistant to furunculosis. We raised pink salmon and a female pink x male chinook salmon hybrid in identical freshwater conditions, transported them in the same tank, separated only by a screen barrier, and reared them in adjoining saltwater pens. The pink salmon must be kept on antibiotic diets throughout the summer and even then have continuous mortalities from furunculosis. The hybrids generally require antibiotic diets during vibrio outbreaks, but we find that they are about 90% more resistant to furunculosis. No epidemics of this disease have been observed in the hybrids. There are serious species specific implications in this study, and we intend to pursue it further.

Kidney disease is carried by the fish from fresh water and generally appears in the first winter in salt water. We have no concrete evidence that it is transmittable in salt water; although we found it in all five species and hybrids of the Pacific salmon that we cultured, it never appeared in epidemic proportions. Kidney disease is a serious problem, especially if a stock is heavily infected in fresh water. Treatment with antibiotics has only been temporarily effective and diseased fish eventually succumb. In my estimation, it is the greatest problem in the total culture of Pacific salmon on a production basis.

To reiterate the difficulties we encountered in culturing pink and chum salmon in salt water, we actually found pink salmon carrying all three diseases simultaneously.

Hybrids and Brood Stocks

The hybrids that I worked with most consistently for the past 3 years were crosses of the pink salmon with the fall and spring chinook salmon. Extreme differences in saltwater adaptability, egg size, age at maturity, disease resistance, fry markings, scale size, time to hatch, growth rates, and behavior manifest themselves as sex-related characters in the hybrids. In this paper, I can only cite a few of the many observations made to date.

I have already mentioned the possible species-related case of resistance to furunculosis. In addition, I have been able to move the female spring chinook x male pink salmon hybrid directly into full sea water with 95% survival within 4 months after they had hatched from the egg, at an average weight of 2.5 g; excellent subsequent growth and 70% survival followed in the first year in salt water. The spring chinook x spring chinook could not tolerate full strength sea water at this size; none survived.

A thorough examination of the fry of a female pink x male fall chinook salmon hybrid revealed that all fish had parr marks or partial parr marks. Pink x pink salmon crosses have no parr marks of any kind.

A mature 2-year-old male of the female pink x male fall chinook salmon was back-crossed with a local female fall chinook salmon from a hatchery. In the resultant progeny, about 1% of the fry had no parr marks.

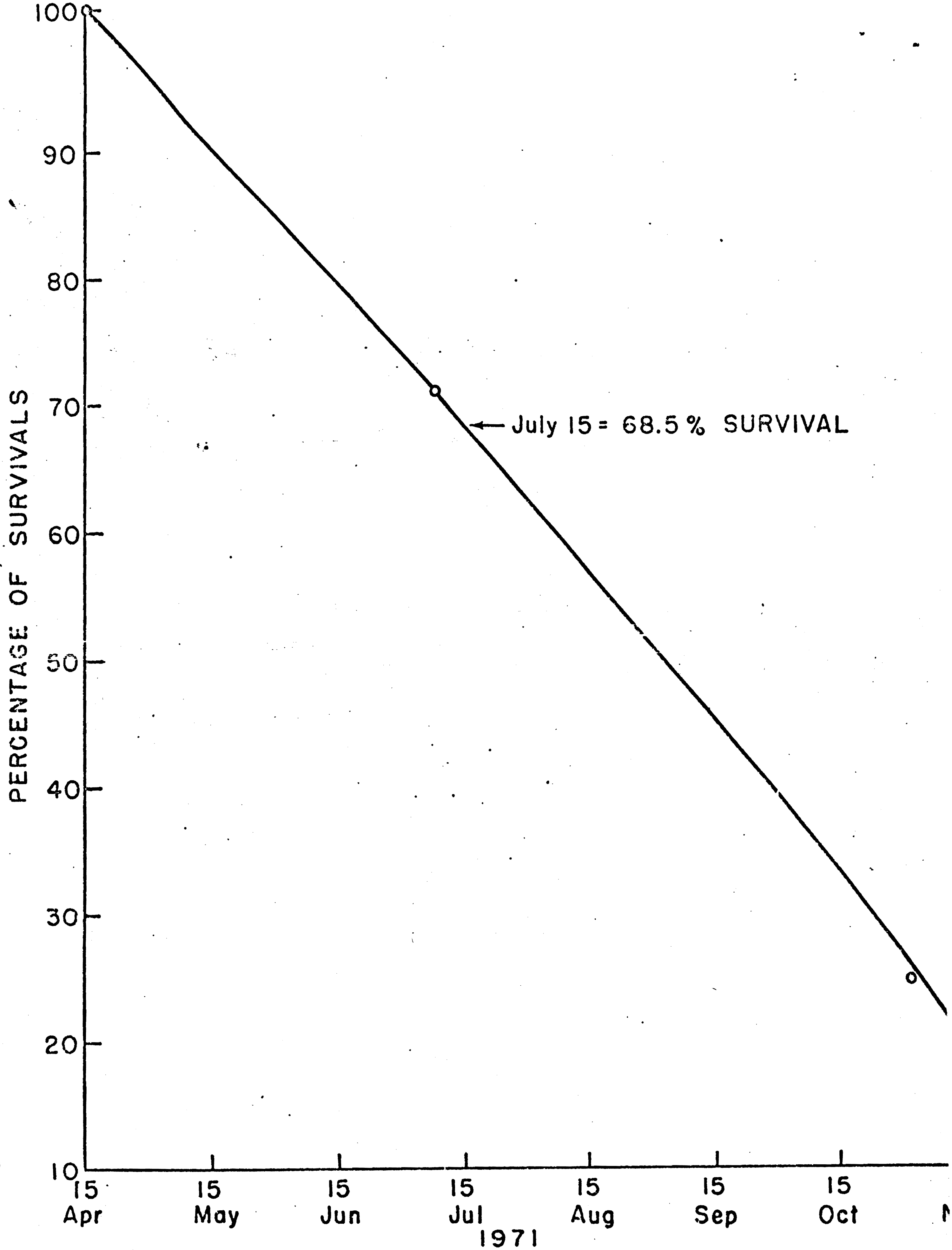

Figure 17. The survival of Alaska pink salmon reared at Clam Bay, Puget Sound.

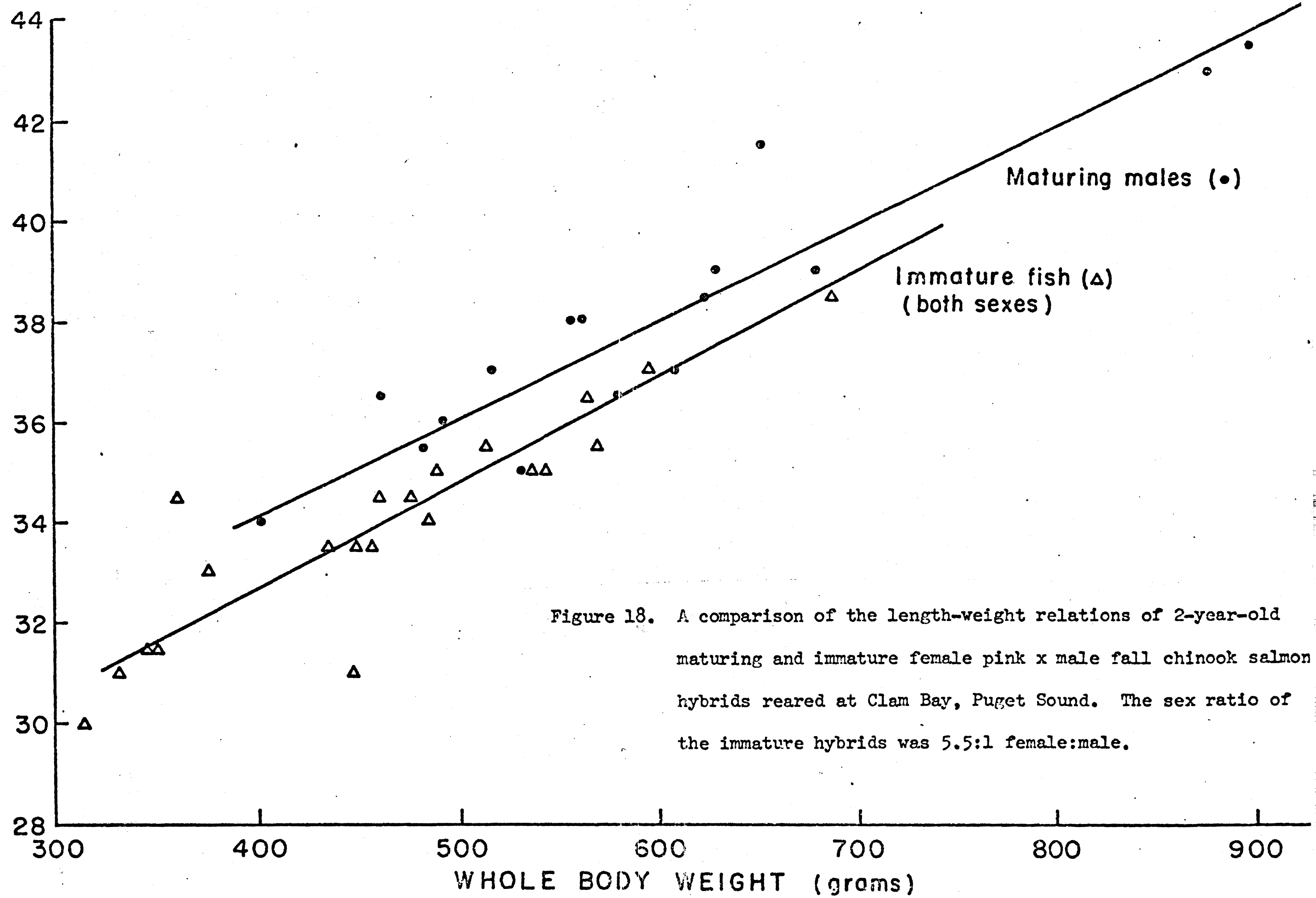

Figure 18. A comparison of the length-weight relations of 2-year-old maturing and immature female pink x male fall chinook salmon hybrids reared at Clam Bay, Puget Sound. The sex ratio of the immature hybrids was 5.5:1 female:male.

A 3-year-old female pink salmon was crossed with a male chinook salmon. Since pink salmon have a 2-year life cycle, we expected all of the fish to mature in 2 years. At the end of the second year, only males matured. Figure 18 depicts length-weight relations of the mature males and some of the remaining hybrids that did not mature. The female to male sex ratio (5.5:1) was oddly disproportionate.

We raised coho salmon to maturity in the pens and spawned them directly from sea water. The results of the first spawning (1970) were poor because the eggs were extremely soft and fragile during all stages of development. Overall survival to the fry stage was less than 5%. Fish of the 1971 brood stock were in much better condition (possibly due to some modifications of the diet), and the survival through hatch ranged from 0 to 80% for various lots. The F_1 progeny are still in the freshwater stages of growth.

Broodstock fecundity of 3-year-old females was about 1,000 eggs (normally 2,500 to 3,500 in naturally reared fish), with average egg diameter of 5.7 mm, which is extremely small. The fecundity of 4-year-old females was about 400 eggs with average diameters of 7.1 mm which is a normal size for wild coho salmon. Three-year-old females that did not mature had large skeins of undeveloped eggs. The change in fecundity in the fourth year leads me to suspect that the eggs were at least partially resorbed during the subsequent winter.

The greatest problem in brood stock development is that we do not have an adequate brood stock diet. This may prove to be a difficult problem to solve, and yet the information will be sorely needed for what is now a budding new industry in Puget Sound.

PRESENT IMPLICATIONS OF PACIFIC SALMON MARICULTURE

Cultured Pacific salmon cannot be expected to grow as rapidly as marine tropical or subtropical fishes. And yet, in terms of ease of culture in saltwater pens, practical rearing densities, and excellent food conversions on commercially available diets, the Pacific salmon appear to have a high economic yield as a cultured marine fish. Moreover, the possibility of intensive raceway culture on a large scale, utilizing the flows from marine thermal power stations, offers potentials for a new approach to salmon culture in colder climates.

The pilot farm experiment which is now completed demonstrated the commercial feasibility of producing a highly marketable Pacific salmon in 12 to 18 months. Our objective is to provide state and federal fishery agencies with the necessary information to enable them to efficiently utilize pen culture techniques for the benefit of the sport and commercial salmon fisheries through resource enhancement. This work has already begun; a preliminary experiment suggests that we can induce local residency and increase the survival of coho and chinook salmon by rearing them in pens in Puget Sound through their first summer in the sea.

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