Review of Recent Progress in Coastal Aquaculture in the United States

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Abstract

The progress in coastal aquaculture in the United States during the last two years is reviewed in detail. Among the fin-fish and shell-fish cultivated commercially, *Crassostrea virginica* and *C. gigas* are the most important, the latter particularly on the Pacific Coast. There are about 74 870 ha of leased oyster beds and about 1.6 million ha of public oyster grounds, with potential for considerable expansion.

One of the important species of prawn suitable for culture is *Macrobrachium rosenbergii*, experiments on which have been in progress in Hawaii. It has been estimated that production up to 2.2 t/ha/year of this prawn is feasible. Interest in research on rearing several marine species of shrimps continuees to grow in the U.S., the important species being *Penaeus duorarum*, *P. aztecus* and *P. setiferus*. Other invertebrates receiving increased attention are *Panulirus argus*, *Homarus americanus*, *Mercenaria mercenaria* and *Mya arenaria*.

The Florida pompano, *Trachinotus carolinus*, has been the object of intense research in the U.S. The important critical problems to be solved for pond production of the fish are temperature control, providing a suitable diet, artificial spawning and rearing of larvae and control of parasites. The other species of fish receiving increased attention in this respect are also mentioned.

1 INTRODUCTION

In a paper to the 13th Session of the Indo-Pacific Fisheries Council, Brisbane, Australia, October 1968, Higgins and Nakamura (1968) defined coastal aquaculture and reviewed the species cultivated, potentially important species, productivity of oysters, and technical and economic problems associated with coastal aquaculture in the United States. The definition of Higgins and Nakamura is adhered to in this report, which reviews the progress that has taken place in coastal aquaculture in the past two years. With the exception of the oyster, coastal aquaculture of marine fin-fish and shell-fish has not been developed for a sufficiently long period, so that data on area and scope of production, manpower, yield, productivity, source of seeds and other information on management and cost factors are either not available or at best preliminary. Therefore, although some factual information on oyster culture and production is presented in this

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account the remaining sections on shrimps, other invertebrates and fish are restricted to reviews of some of the experiments and problems associated with attempts to culture them in the United States. For further details on coastal aquaculture in the United States the works of Iversen (1968), Ryther (1968), Ryther and Bardach (1968) and Bardach (1968b) may be consulted.

2 OYSTERS

Among the species of fin-fish and shell-fish cultivated commercially in the United States, the American oyster, *Crassostrea virginica,* is by far the most important. The Pacific oyster, *Crassostrea gigas,* is another species of considerable importance, particularly along the Pacific Coast.

2.1 Area and scope

According to Ryther (1968), there are about 185 000 acres (74 870 ha) of leased oyster beds and about 4 million acres (1.6 million ha) of public oyster grounds in the United States. The potential exists for a very considerable expansion of oyster culture. Estimates say that around Long Island, New York, there are at least 9 million acres (3.6 million ha) of approved shell-fish producing grounds, but only 40 000 acres (16 190 ha) are currently available for lease. However, only a small fraction of the available lease properties is actively farmed. On the Pacific Coast, Washington, which produces over 80 per cent of the Pacific oyster, has large areas of tidal flats suitable for oyster culture (Iversen, 1968), and suitable grounds are also available in California.

2.2 Manpower

It is difficult to obtain accurate estimates of the manpower presently engaged in oyster culture, because of the many small hatcheries and farms. Ryther (1968), in describing the operation of a hatchery on Long Island Sound, stated that it required a trained professional staff of 2-4 people and an additional 5-10 workers during peak activity. This commercial hatchery currently leases about 2 600 acres (1 050 ha) of oyster beds in waters with a mean depth of 2-35 ft (0.9-10.7 m).

2.3 Yield and productivity

Webber and Riordan (1969) have pointed out that in the U.S.A., public grounds are unmanaged and the yield is poor but private oyster farms, where oysters are moved from setting grounds to growing grounds and predators are controlled, produced on average nearly 20 times as much as the unmanaged grounds. In comparing total production between leased and public grounds, Ryther (1968) noted that some 15 430 short tons (14 000 metric tons) of oyster meat are produced from 185 000 acres (74 870 ha) of leased or privately owned beds, the same amount as that produced on about 4 million acres (1.6 million ha) of public oyster grounds. Bardach (1968a) reported that cultivation of stocked or natural populations of oysters on public grounds yielded an average of 8 lb/acre/year (9 kg/ha/year), whereas stocked populations on leased grounds under intensive cultivation produced 4 460 lb/acre/year (5 000 kg/ha/year).

2.4 Source of seed

Ryther (1968) noted that natural seed oyster production in the northeastern United States is presently very restricted and undependable because of pollution, dredging and filling, which change the ecology of the oyster's natural environment. To alleviate the shortage, farmers have attempted to raise seed oysters imported from the Central and South Atlantic States, but had little success because the oysters, although of the same species, apparently could not adapt to the environmental conditions of the north. The result is that, at present, four commercial hatcheries are producing seed oysters for the farmers of the northeastern states.

In the Pacific Northwest, attempts to establish spawning stocks of the Pacific oyster, *C. gigas*, have been unsuccessful, although the oysters grow very well in the tidal flats along the coast of Washington (Iversen, 1968). Spawning has been reported to be successful on a few occasions in some areas, but the supply of seed oysters is highly irregular. As a result, the culture of Pacific oysters, which may reach 8 million pounds (3 600 metric tons) annually, is based almost entirely on seed oysters imported from Japan.

In those states bordering the Gulf of Mexico, the spat of the American oyster are collected by setting out oyster shells in oyster spawning areas (Iversen, 1968).

2.5 Culture management

The operations of oyster hatcheries, as we know them today, are briefly described below (Ryther, 1968; Davis, 1969). In commercial hatcheries, oysters are spawned under controlled conditions. Sexually mature adult oysters, selected from the growing beds, are held in the hatchery at 10°C (50°F), then conditioned for spawning by slowly raising the temperature and holding the oysters at 18°C (64.4°F) for 2-4 weeks. When the temperature is raised to 25°C (77°F), the oysters begin spawning. It has been estimated that a single female may release 70 million eggs at one spawning.

Fertilized eggs are transferred to rearing vats until development to the straight-hinge stage; the larvae then undergo screening until only the larger, rapidly growing individuals, representing roughly 20 per cent of the total production, remain. Transferred to tanks holding specially prepared water of natural or inoculated algal culture and fertilizer, the larvae start to feed on the algae. If the culture is not sufficiently dense to supply the needs of the oyster larvae, supplemental direct feeding of algal culture is required. Species used for the feeding are flagellates *Isochrysis galbana*, *Monochrysis lutheri*, and *Rhodomonas* sp., and experience has shown that a mixture of at least two different species is required. The rate of feeding of algal culture is about 2 000 cells/larvae/day.

When the larvae are ready to set, usually in about 10-15 days, they are transferred to plastic tanks which contain a layer of specially selected, screened and washed oyster shells. The larvae attach to the shells as they metamorphose. The cultch with spats attached, is then placed in polyethylene net bags hung on racks, and immersed in post-setting tanks. The larvae are fed water containing algal bloom; high temperatures and supplemental feeding result in rapid growth of the young seed oysters. After a few days, the seed oysters are about 0.06-0.12 inch (1.5-3.0 mm) in diameter. Only then are the racks with shell bags attached, transferred outside to the dock, where they are placed on a floating raft. Seed oysters are kept in open waters for about 2-3 additional weeks until they reach a size of about 0.25-0.50 inch (6.3-12.7 mm). The entire hatchery operation from spawning to fingernail-size seed oyster requires 4-6 weeks. Because of the seasonal variation in the water temperature hatchery operations are restricted to late spring and summer.

Year-round hatchery production for seed oysters is a distinct possibility (Ryther, 1968). At Long Island, water used by a local power company to cool its machinery is discharged into a 7-acre (2.8-ha) lagoon. The discharged water being 7°-10° C (12.6°-18° F) warmer than the intake water, is very beneficial for clam and oyster growth. Preliminary tests have shown that oysters and hard clams can not only survive, but also grow exceptionally fast in the cooling water. This cooling water is nontoxic and has a high nutrient content to support a luxuriant growth of microscopic algae. The lagoon may prove to be better for year-round seed oyster production after all the tests are completed. High midsummer temperatures, reaching 30°-32° C (86°-89.6° F) proved beneficial as the seed oyster showed exceptionally rapid growth, contrary to the belief that the high temperatures would arrest growth and might even be lethal.

The rate at which seed oysters are planted on commercial beds is about 500 bushels/acre (43.5 kl/ha) (Ryther, 1968). After 1 year on the bottom, the seed oysters have increased in size to 5 000 bushels (176.2 kl) and redistributed on 5 acres (2 ha) of oyster beds. By 3 years, the density is about 10 000 bushels (352.4 kl) and again the oysters require redistribution on 10 acres (4 ha) of bottom. Projections at this rate of planting indicate that 500 bushels of seed oysters/acre (43.5 kl/ha) could reach 500 bushels of marketable oysters/acre.

Not all the Atlantic Coast oyster farmers require hatchery produced seed oysters. Along the gulf and south to mid-Atlantic coasts, the oyster farmers have no difficulty in obtaining a successful set of seed oysters; the adults, however, are susceptible to widespread infection and mortality (Ryther, 1968). In the Hawaiian Islands, private fishpond owners buy seed and adult oysters which have been removed from the oyster beds in West Loch, Pearl Harbour, Hawaii.

2.6 Cost-benefit factors

Cost-benefit data are not readily available for the United States oyster-culture industry, but a typical hatchery operation used as an example by Ryther (1968) should provide some idea of the capital investment required. For a commercial hatchery operation leasing about 2 600 acres (1 050 ha) of oyster beds, the capital investment required would be about $100 000-$200 000.

Under controlled conditions, the income from a privately leased oyster ground could be substantial. With the current wholesale prices of oysters at $18/bushel ($0.51/litre), a production of 500 bushels/acre/year (43.5 kl/ha/year) would generate a gross income of $9 000/acre ($22 240/ha). Estimates place the production of oysters from leased grounds in the United States at an average of about 0.66 short ton/acre/year (1.48 metric tons/ha/year), whereas the public grounds produce only 0.03 short ton/acre/year (0.07 ton/ha/year). These national averages, when compared to the projected production from a private operation, represent only about 1/30 and 1/600 of the projected yield. The difference is very striking. Ryther and Bardach (1968) pointed out that populations of oysters on public grounds yielded an average of 7.9 lb/acre/year (9 kg/ha/year) worth $15/acre ($38/ha), whereas the best yield on leased grounds under intensive cultivation reached 4 460 lb/acre/year (5 000 kg/ha/year) worth $8 498/acre ($21 000/ha).

2.7 Problems

Much of the research in oyster culture now being done in the United States revolves around the merits of new culture methods. Loss of oyster grounds suitable for culturing, shortage of oysters in many areas, the increased value of oysters and commercial interest in seed oyster production have stimulated research into culture techniques (Shaw, 1969). In the past decade, the major interest has centred on the merits of bottom culture as now practised and off-bottom culture from rafts, platforms, trays, or other methods used in other countries.

The Maine Department of Sea and Shore Fisheries has experimented with strings of scallop shells suspended from rafts as spat collectors (Shaw, 1969). Shaw also reported that investigation of off-bottom oyster culture in Oyster Pond River, Chatham, Massachusetts has shown excellent growth of oysters that settled on scallop and oyster shells strung on wires and suspended from a log raft. In one experiment, 70 per cent of the oysters suspended for 1.5 years and then planted on the bottom for another year were marketable, whereas wild oysters grown on the bottom required 4-5 years to attain the same size. In reporting the research results from other states, Shaw (1969) noted that at Fishers Island, New York, 55 000 strings of scallop shells were suspended from 130 rafts in a 20-acre (8-ha) salt pond, and estimated production reached 25 million seed oysters annually; at Oxford, Maryland, where extensive studies on off-bottom cultures have been conducted since 1960, the results have shown that when suspended shells became fouled before the oyster larvae were ready to attach, they failed to catch a good set. Other significant findings were that oysters near the surface grew faster; that many oysters on the bottom portion of the strings were dead, and that oysters on strings held horizontally grew faster than those held vertically.

Investigations in North Carolina also proved of interest to oyster culturists (Shaw, 1969). Among the findings were, that asbestos plates were superior to plastic plates as spat collectors and that growth and number of oysters were best on plates measuring 8.25 x 8.25 inches (21.0 x 21.0 cm). Other results also showed that vertical spacing of 6-10 inches (15.2-25.4 cm) was superior to spacing of 2-4 inches (5.1-10.2 cm) and that strings that were aired 4 hr/day had greater survival and growth of oysters.

On the Pacific Coast in California, off-bottom culture of oysters is practised commercially on a small scale, the major centre for commercial off-bottom culture being Humboldt Bay (Shaw, 1969). Oysters farmed off the bottom in the bay reach marketable size in 18-24 months whereas those reared on the bottom require an additional 1-2 years to reach market size.

In Washington, seed oysters of *C. gigas* are caught commercially off-bottom in Dabob Bay. Settings of commercial levels were obtained for 10 out of 14 years. Results of tests have shown that setting is greater on rack-hung strings than on those hung from floats (Sayce and

Tufts, 1968). Small-scale, pilot-farm studies on Pacific oysters, *C. gigas*, and clams by fishery scientists at the University of Washington have shown that unspaced oyster shells treated with Sevin (an insecticide) collected more oyster larvae than the other cultch materials such as egg crate fillers coated with cement or with a cement-Sevin mixture, and plain untreated oyster shells (Chew, Nosho, and Lipovsky, 1970). The experiments were designed to study the possibility that low levels of insecticide toxicity function as an attraction to oyster larvae.

Experiments in Hawaiian fishponds have shown that seed oysters grow best when cultured in the surface layers of water (Hawaii, 1970). Seed oysters, obtained from the oyster beds in Pearl Harbour and transferred to fishponds, reached commercial size of 3 inches (7.6 cm) in a year's time when reared in trays.

Off-bottom culture of oysters in the United States is still beset with problems (Shaw, 1969). Many areas where off-bottom culture can be carried on are presently being used for recreation and navigation. Methods to control mortalities caused by fish, crabs and worms must also be developed, and fouling of the suspended shells by barnacles, bryozoans, and tunicates must be studied. In addition to predator- and disease-caused mortalities, Ryther and Bardach (1968) pointed out that the effects of man-made changes in the environment, the use of primitive methods and poor management practices are other problem areas that require study. Davis (1969) reported that only recently have genetic studies been initiated with the intent of producing new races of oysters that are fast growing, disease resistant, high in meat content, and tolerant to a wider range of physical factors.

Ryther (1968) believes that the prospects of large-scale raft or platform culture of oysters in the crowded waters of Long Island Sound are rather remote because of the heavy demand of this area for recreational use. Other major problems appear to be the irregular shape of the shell and heavy fouling, both of which make off-bottom cultured oysters unsuitable for the half-shell market. He suggests that perhaps a combination of two methods—off-bottom culture in private ponds during the first year to reduce mortalities from predation and silting and to obtain rapid growth, and bottom culture for shaping and final growth to market size—may prove to be a satisfactory solution.

In recent years, there has been a spectacular tenfold increase in oyster production from Long Island Sound, off Connecticut, and the factors responsible for this increase, according to MacKenzie (1970), were the efforts by government and industry scientists to develop better oyster-setting beds and new methods to control the major causes of mortality, and produce seed oysters under controlled conditions at the hatcheries. The use of improved equipment and scuba diving gear to examine the oyster beds has also contributed significantly to better production.

Predation by starfish and oyster drill and silting are cited as some of the major causes of mortality on the oyster beds. It has been estimated that prior to 1966, starfish were responsible for mortality of 60-70 per cent of the young oysters, but by dragging cotton mops over the planted beds to determine the extent of starfish invasion and then applying quicklime at the rate of 1 600-2 000 lb/acre (1 793.4 - 2 241.7 kg/ha) to the infested areas, the oyster farmer can reduce starfish predation to only 5-10 per cent of the seed oysters (MacKenzie, 1970). In experiments to control predation by oyster drills, the National Marine Fisheries Service Biological Laboratory at Milford, Connecticut, used Polystream, a mixture of hydrocarbons, over the beds and was successful in destroying about 85 per cent of the drills. Seed-oyster mortality was reduced to about 2-5 per cent.

Silting causes suffocation among young oysters and although the average mortality rate from suffocation is about 20 per cent, it can be very serious with mortalities reaching upward to 75 per cent (MacKenzie, 1970). Silt accumulates up to 2 inches (5.1 cm) in winter covering the dormant oysters, but suffocation does not occur until the following spring when the oysters attempt to pump water as a result of an increase in their metabolic rate. Oyster companies have now learned to reduce silt mortalities by transplanting the oysters out of heavily silted areas earlier in the year.

The improved methods of controlling mortalities have been reflected in the increase in oyster production. Whereas oyster companies previously obtained 1 bushel (35.2 litres) of market oysters (200 oysters) from 1 bushel of seed oysters (5 000 seed oysters), nowadays the companies are obtaining yields of 10 or more bushels (352.4 litres) from 1 bushel of seed oysters (MacKenzie, 1970).

Other experiments on growth of oyster spats at the Milford Laboratory have shown that oyster spats have a better growth rate when reared in unfiltered, flowing sea water than recirculated water (FAO, 1970). When feeding was intensified, the spats showed no improvement in growth rate in recirculated water, but showed a growth rate 2-2.5 times greater in the unfiltered, flowing sea water.

3 SHRIMPS

The culture of shrimps, which has generated tremendous enthusiasm among mariculturists, offers the best possibilities for commercial culture among crustaceans. The insatiable market demand for shrimp in the United States and the high price paid for it have stimulated State and Federal Government agencies and industry to develop methods for culturing shrimp.

One of the potentially important species of prawns mentioned by Higgins and Nakamura (1968) as being suitable for aquaculture, is *Macrobrachium rosenbergii*. Although the adults of this species are fresh-water forms, the larvae require brackish water for survival; therefore, it is discussed here as a species suitable for coastal aquaculture.

In the United States, the Hawaii Division of Fish and Game has taken the initiative in conducting experiments dealing with *M. rosenbergii* culture. In August 1964, the first lot of *M. rosenbergii*, consisting of four mature males and four gravid females, was imported into Hawaii through the cooperation of the Fisheries Division of Malaysia (Fujimura, 1966). Ten males and 18 females followed in additional lots. From this original breeding stock, the Division of Fish and Game produced and reared to maturity more than 3 000 second-generation prawns and by 1969 had produced an estimated 700 000 prawns (Hawaii, Department of Land and Natural Resources, 1970). Many of the details of rearing these prawns on a commercial scale were worked out at the same time. Briefly, the procedure is to place the newly hatched larvae in phytoplankton-rich "green" water which has a salinity of about 18 ppt (Fujimura, 1966). After 12 days, the larvae are transferred to clear water of the same salinity. In addition to their phytoplankton diet, the larvae feed on *Artemia salina* nauplii and ground fish flesh. The post-larval stage is reached in about 30 days; the juveniles are then farmed out to owners of fresh-water ponds for rearing to marketable adults. Having demonstrated that sufficient numbers of young prawns can be propagated to supply commercial prawn farmers, the Hawaii Division of Fish and Game is now concentrating on methods to reduce production costs from the present $6.47/1 000 prawns to a more reasonable cost of about $2.00/1 000.

Nine owners of private fresh-water ponds throughout the State of Hawaii have indicated interest in test-rearing young juvenile prawns to marketable size. The ponds, which vary in size from 0.25 to 6 acres (0.1 to 2.4 ha) and have a combined surface area of about 10 acres (4.0 ha) were stocked with a total of 207 000 juveniles. Faster growth rates have been achieved by supplemental feeding. Now marketing of prawns can be done after a little more than 1 year, whereas previously it required 2 years. Fujimura (1970) estimates that production of up to 1 ton/acre/year (2.4 metric tons/ha/year) is feasible.

Interest in research on rearing several marine species of shrimp continues to grow in the United States. Bardach (1968a) reported that the Biological Laboratory of the National Marine Fisheries Service in Galveston, Texas, the Bears Bluff Laboratory of the South Carolina

Wildlife Resources Commission and the Institute of Marine Sciences of the University of Miami in Florida are among the agencies that have taken the initiative in carrying out shrimp culture experiments. Broom (1969) reported that pond culture experiments of shrimp were started at Grand Terre Island, Louisiana, in 1962.

The culture of penaeid shrimps is still in the experimental stage in the southeastern United States. Idyll, Tabb, and Yang (1969) have noted that long-term research has started on the intensive culture of pink shrimp, *Penaeus duorarum*, with the support of the Armour Company, the United Fruit Company and the National Science Foundation under its "Sea Grant" programme. Facilities include four 0.25-acre (0.1-ha), two 0.5-acre (0.2-ha), and one 1-acre (0.4-ha) ponds. In addition, there will be 16 concrete outdoor larval rearing tanks, each with a capacity of 20 million tons (18.1 million metric tons). During the first year shrimps were successfully reared from egg to pond-stocking size. In Louisiana, Broom (1969) reported that brown shrimp, *Penaeus aztecus* and white shrimp, *P. setiferus*, were cultured experimentally in 0.25-acre (0.1-ha) ponds. Juveniles and postlarvae, obtained from several sources, were stocked at different rates and fed several types of feed. Tests showed that the best feeding rates were 5 and 10 per cent of their body weight at a stocking rate of 20 000/acre (49 400/ha). The annual production realized under this experimental condition ranged from 40 to 809 lb/acre (44.7-906.2 kg/ha) and food conversion ratios varied from 1.7 to 9.7. Other information obtained through the experimental culture operation showed that higher mortalities occurred in ponds stocked with postlarvae than in ponds stocked with juveniles; higher mortalities were also recorded in unfed ponds than in ponds receiving supplemental feed.

Using a method similar to that first described by Hudinaga [Fujinaga] of Japan for culturing larval shrimp, Cook and Murphy (1969) recently were successful in rearing relatively large numbers of penaeids in the laboratory. Slight modifications of this procedure have increased the yield of post-larval penaeid shrimp reared from eggs spawned in laboratory containers. Among the six species cultured were the commercially important brown, white and pink shrimps.

The method adopted by Cook and Murphy (1969) depends on wild stocks for the supply of females in spawning condition. Ripe penaeid shrimps, easily identified, are placed in 500- or 275-gallon (1 890- or 1 040-litre) round polyethylene tanks at the rate of one or two per tank. Only about one-third spawn viable eggs, usually during the first night after they are brought to the laboratory. After spawning, the adults are removed to prevent their eating the eggs, which hatch in 12-16 h. The emerging larvae do not feed during the nauplial stage; feeding begins at the protozoal stage. Among the algae used successfully for feeding the protozoa are *Skeletonema costatum*, *Thalassiosira* sp., *Cyclotella nana*, *Phaeodactylum* sp., *Dunaliela* sp., *Gymnodinium splendens*, and *Exuviella* sp. During the mysis stage, they are fed newly hatched brine shrimp. From the results of the experiments, Cook and Murphy (1969) learned that temperature affected the rate of development throughout the larval stages. In water of 30 ppt salinity, brown shrimp reached the first larval stage in an average of 17 days at 24°C (75.2°F), 12.5 days at 28°C (82.4°F) and 11 days at 32°C (89.6°F). Highest survival of nauplii occurred at 24°C (75.2°F), and as the shrimp passed through the protozoa and mysis stages, survival usually increased with an increase in temperature. Salinities above 35 ppt or below 27 ppt were lethal to the larvae. Cook and Murphy (1969) found that food consisting of a mixture of *C. nana*, *Isochrysis galbana*, *S. costatum*, and *Thalassiosira* sp., or *Thalassiosira* sp. alone probably were the best. These investigators have just begun to study the physiological requirements and tolerances of larval shrimp, but they feel that the yield of postlarvae per volume of water should increase significantly as they learn more about the effects of temperature, salinity, and feeding rates on larval density.

Intensive research on shrimp culture is continuing in other parts of the United States. The Skidaway Institute of Oceanography in Savannah, Georgia, has become involved in experimental work on adapting the flowing water intensive culture techniques used in salmon and trout culture to the rearing of channel catfish, penaeid shrimps, and flounder (Andrews, 1970). One of the major objectives will be to develop a suitable pelleted shrimp diet using natural ingredients. Also related to nutrition will be research on protein, mineral, vitamin, lipid, carbohydrate, and amino acid requirements of the shrimp. Environmental and physiological experiments include studies on the effects of light, temperature, salinity, water input, water quality, and stocking rate on growth, efficiency of food conversion, and general health of the shrimp.

At the University of Washington, Price and Chew (1969) reported their success in artificially rearing large "spot" shrimp, *Pandalus platyceros* from egg to subadult stages. Using a closed recirculating salt water system, they determined that eggs collected from gravid females and incubated at 15°C (59°F) hatched earlier than at 11° and 13°C (51.8° and 55.4°F), but the larvae died shortly after hatching. Best survival of larvae was obtained at 11°C (51.8°F). The larval "spot" shrimp were fed *A. salina* nauplii; the post-larval stages were fed a supplementary diet of ground fish flesh, because the nauplii alone were found to be inadequate. Other studies by Price and Chew (1970) included the culture of *Pandalopsis dispar*. Eggs collected from dead, egg-bearing females caught in trawl tows were successfully hatched in specially designed containers. Detached eggs, hatching earlier than those on the female, produced normal larvae; it was determined from the experiments that flow rates within the egg-hatching containers were more important than temperature in determining hatching time.

The fact that private industry has made tremendous progress toward the goal of culturing shrimps on a commercial scale can be seen in a recent report by Hull (1970). Marifarms, Inc., a commercial 2 500-acre (1 012-ha) shrimp farm in St. Andrews Bay, Panama City, Florida, is scheduling the first harvest of cultured shrimp in October 1970. Marifarms, employing about 60 people, concentrates its present efforts on producing shrimp for the food market and in the future hopes to become a supplier of post-larval shrimp to shrimp farmers. The procedure being used there at present is to collect gravid females of white, pink and brown shrimps in the wild and to induce spawning in captivity, although the farm is licensed to use the Japanese-developed Fujinaga process has the expertise necessary for raising and mating its own brood stock.

On reporting the culture method used at Marifarms Hull (1970) noted that after spawning, the young shrimp are nursed through several larval stages on specially cultured mixtures of phytoplankton, mainly diatoms. Survival of the young has averaged about 57-58 per cent, although a survival rate of 95 per cent was achieved in individual lots. After attaining a size of about $<$ 0.1 oz (0.02 g) or 0.8 inch (20 mm) in about 3 weeks, the post-larvae are released into the nursery area.

Confined within the 2 500-acre (1 012-ha) main range is the 250-acre (101-ha) nursery area and in it the postlarvae undergo further growth; at the end of 3 months, they are released into the main range. From the time of hatching to harvesting requires about 7 months. The water of the main range is fertilized with a standard, commercial nitrate and phosphate fertilizer commonly used on lawns. Plankton and rooted grass flourish after fertilization and form the basis of the shrimp's diet; supplemental feeding includes ground-up trash fish.

Hull (1970) reported that the main range, prior to receiving the young shrimp, is cleared of predators by two methods: by encouraging the local fishermen to go into the range to harvest the fish and by using rotenone. Potassium permanganate is used outside the fenced range to neutralize excess rotenone; weekly antifouling patrols clear the nets along the entire seaward perimeter of other fouling organisms.

Managers of Marifarms have not determined the best way to harvest the shrimp (Hull, 1970). The yield is not expected to be large; a reasonable expectation is 300-500 lb/acre (336-560 kg/ha), but the first harvest is not expected to reach this level.[1] Hypothetically, if at a size

[1] The first harvest in 1971 was reported to average 300 lb/acre (336 kg/ha).–Ed.

of 26-30 shrimps/lb a yield of 400 lb/acre (448 kg/ha) were feasible and could be sold for $1.00/lb ($2.20/kg), then a farm 2 500 acres (1 012 ha) in size could realize a gross income of $ 1 000 000.

4 OTHER INVERTEBRATES

4.1 Spiny lobster

Another crustacean of high monetary value receiving increased interest as the object of mariculture is the spiny lobster, *Panulirus argus*. Provenzano (1969) has reviewed studies on larvae of the spiny lobster and the sand or slipper lobster (Scyllaridae) and has summarized results of importance to future studies.

In 1963, several attempts to rear phyllosoma larvae of a number of different species of lobster met with moderate success (Provenzano, 1969). Most effort was concentrated on phyllosomas of various sand lobsters because of their availability at that time. Studies on larvae of spiny lobster, carried on in conjunction with those of sand lobster larvae, showed that at temperatures above 20° C (68° F) spiny lobster larvae passed through as many as eight or nine moults and that some lived as long as 9 or 10 weeks. Growth was markedly slower after the first few moults, however, and, after 2 months, the larvae were much less developed than those found in their natural environment.

A major obstacle to rearing the phyllosoma larvae of spiny lobster to metamorphosis has been the providing of adequate food, particularly to the later-stage larvae. Brine shrimp, *A. salina* used extensively for feeding the larvae, did not satisfy the nutritional requirements of the later-stage larvae.

Taking a radically different approach to the problem of culturing spiny lobster, Ingle and Witham (1969) suggested that culturing should start after metamorphosis. Their studies have shown that at about the time of metamorphosis, the puerulus or first-stage postlarva migrates into shallow-water sanctuaries of coastal bays and lagoons. They also reported that phyllosomas are rarely found in plankton samples collected in bays and lagoons; the first and later stages, however, are readily found in these areas. Artificial habitats similar to those in which the postlarvae of spiny lobster are found were developed and although some of them did not attract any postlarvae, a few did and these were very dependable with consistent recruitment. Habitats occupied by later post-larval stages were also simulated; these were also found inhabited.

With this knowledge about the behaviour of the post-larval stages, Ingle and Witham (1969) proposed a method of artificial cultivation that eliminates the time-consuming and costly procedure of rearing phyllosomas from eggs. The procedure is to (1) locate a protected bay in which postlarvae can be obtained, (2) install an artificial habitat to attract the postlarvae, (3) remove postlarvae from the habitat to holding ponds daily, (4) provide large quantities of small articles of a porous texture as a sanctuary for the juveniles, and (5) feed regularly. After the postlarvae have passed through the smallest, more vulnerable stages, the animals could be kept in the pond until ready for marketing, released into larger enclosures to forage and be fed on a supplemental diet, or released into public fishing areas.

4.2 American or Maine lobster

The American lobster, *Homarus americanus,* is one of the most popular decapods marketed in the United States and commands a premium price because of the decreasing yield in recent years (Hughes, 1968). Researchers at the lobster hatchery, established by the Commonwealth of Massachusetts on Martha's Vineyard off the heel of Cape Cod, have been intensively studying the possibility of culturing the lobster commercially. The present practice is to collect egg-bearing females from lobstermen and to allow them to hatch their eggs in hatching tanks. Hatched lobster fry are collected from these tanks and placed in special rearing tanks until the bottom-crawling stage. Water circulators in the rearing tanks keep the water moving, thereby preventing accumulation of larvae in the corners. The fry are maintained on a diet of finely ground clams or frozen adult brine shrimp. Survival rate has been estimated to be about 30 per cent, although in one season the survival rate was as high as 43 per cent. Causes of mortality have been traced to supersaturation of dissolved nitrogen in the water, which causes fatal gas diseases, to lethal ions of metals such as copper, to copper- and lead-based paints, and to insecticides in the vicinity of the tanks. When the lobsters reach the fourth moulting stage, they are released in selected areas along the coast of Massachusetts. Little is known about the fate of the hatchery-reared lobster after release.

Data collected by hatchery biologists over the years have indicated the possibility of commercial rearing of lobster from egg to adult (Hughes, 1968). One of the most important breakthroughs to potential lobster culture involves the production of second generations by hatchery-reared adults. Until recently, none of the successfully mated females produced fertilized eggs; however, by deepening the water in the female's tank to allow coverage of at least 18 inches (45.7 cm), hatchery biologists found that the female successfully laid and fertilized her eggs. Other data vital to a commercial lobster culture operation show that lobsters from the same batch grow at different rates, that temperature influences the lobster's metabolic rate so that they reach marketable size in less time, and that hatchery lobster can reach legal size in 3 years compared to 6 years in the ocean. These data all indicate that lobster culture is a definite possibility.

4.3 Clams

The clam is another invertebrate that has great potential for sea farming. Iversen (1968) reported that the hard clam, *Mercenaria mercenaria*, or "quahog," is farmed only to a limited extent in the United States, mainly along the Atlantic coast. The hard clam and the soft clam, *Mya arenaria*, or "long-necked clam," are both suitable for farming, although they are not as desirable as oysters as the object of sea farming because of their slower growth rate, the difficulty encountered in collecting seed, and the lower market price. Experiments carried out at Florida State University revealed that the hard clam grows rapidly in the warmer Florida waters and that marketable size of 2.5 inches (6.4 cm) can be attained in 2 years instead of the 5 years required in colder waters.

5 FISHES

The farming of marine species of fish has not progressed at the same rate as the farming of fresh-water species in the United States. One of the species which has been the object of intense research is the Florida pompano, *Trachinotus carolinus*.

In a report on the progress and potential of fish mariculture in the United States, Iversen and Berry (1969) presented new data on availability and ecology of beach-caught fry of the Florida pompano, a species which they believe has great farming potential in terms of market value, palatability, consumer demand, and research progress (Berry and Iversen, 1967). Iversen and Berry (1969) cited the work of Moe *et al.* (1968) and that of Finucane (1968) as contributing substantially to our knowledge of the biology, ecology, and farming potential of the pompano.

Iversen and Berry (1969) found that the Florida pompano fry were most abundant on low-energy beaches (those with a long gradual slope), whereas few fry were found on steep, high-energy beaches with heavy surf. They also found higher abundance of pompano fry in conjunction with falling tides and noted that abundance was greatest from about New Smyrna Beach north to St. Augustine on Florida's east coast.

Marine scientists at Batelle Memorial Institute's Florida Marine Research Laboratory near Daytona Beach have found from their studies on pompano culture, that feeding pompano five times a day at a rate of 10 per cent of their body weight per day, produces very rapid growth (Anon., 1968). Batelle scientists, who bave been able to triple the size of surf-caught fingerlings after only 2 months in captivity, used four rectangular tanks 50 x 80 ft (15.2 x 24.4 m) and two circular tanks 20 ft (6.1 m) in diameter, all of which were 6 ft (1.8 m) deep, for their culture experiments.

Finucane (1970) also reported rapid growth of pompano in captivity; the best growth during a 6-month period was obtained by feeding a commercial trout feed. Stocked at a rate of 1 000 fish/acre (2 470/ha) pompano in ponds grew at a rate of 1.25 inches (3.2 cm) and gained more than 1 oz/month (28.4 g/month). Experiments with juveniles at St. Augustine, Florida, showed that with proper diet and control of water quality, the fish can be grown to a weight of about 1 lb (453.6 g) in less than a year.

Florida pompano can withstand extreme turbidity, rapid changes in pH and oxygen concentration as low as 3 ppm (Finucane, 1970). Other qualities which favour pompano for farming are their tolerance to close confinement and rapid recovery from injuries in salt water impoundments.

In experiments at the Miami Seaquarium, Iversen and Berry (1969) found that mortality of the young pompano varied, but they believe that death rates can be held to less than 10 per cent by minor improvements in the food and artificial environment and by adequate preparation to meet emergencies such as those resulting from mechanical failure, human error, epizootics or hurricanes. They also found beach-caught juveniles infested with cestodes, nematodes, monogenetic and digenetic trematodes, and sporozoans. To control the monogenetic trematodes, which damaged the epithelial layers of the gills and apparently interfered with respiration, Iversen and Berry (1969) applied routine prophylactic treatment with copper sulphate.

Temperature has been shown to be another of the critical factors affecting pond production of Florida pompano (Finucane, 1970). Experiments on pompano culture at the National Marine Fisheries Service Biological Laboratory at St. Petersburg Beach, Florida, revealed that the fish cease feeding at 13.9° C (57° F) and die at 10° C (50° F). Captive fish have survived in temperatures from 13.9° to 32.8° C (57° to 91° F), but water temperatures of 23.9°-25° C (75°-77° F) were reported to be ideal for good growth of the juveniles. Finucane (1970) reported that one of the best areas for pompano culture is the Florida Keys, where water quality and temperature are ideal.

Providing a suitable diet appears to be another critical problem in pompano culture (Finucane, 1970). None of the diets tested sustained maximum growth and low mortality and a unique diet especially formulated for pompano is needed before commercial farming on a large scale is possible.

To maintain commercial production of Florida pompano, it is also desirable to induce spawning and develop hatchery techniques to rear the fish from eggs to marketable size. Finucane (1970) reported that spawning has been induced by injecting ripe fish with chorionic gonadotrophin, but the spawned eggs have not been hatched as yet.

Iversen and Berry (1969) believe that intensive research should be started on artificial fertilization and on the rearing of larvae through the critical period following the yolk-sac stage. Subsequent genetic experiments could concentrate on improving the stocks with respect to rapid growth and disease resistance.

Not all the problems associated with pompano culture are technological or scientific in nature. Hull (1968), reporting on his observations on fish farms during a visit to Florida, emphasized that legal problems will undoubtedly hinder the rapid development of mariculture within the State. Large-scale capture of pompano fry, removed at a rate of 15 000-20 000 fry in one seining operation, has brought not only protests from the people living along Florida's east coast, mainly around St. Augustine, but also from sport and commercial fishermen (Hull, 1968; Iversen, 1969). Reacting to these protests, the Florida Board of Conservation recently imposed a restriction on the number of young that can be collected on public beaches, to stock private pompano ponds (Iversen, 1969). Hull (1968) stated that for pompano culture to succeed on a large, commercial scale, the fish will have to be spawned and cultured in captivity. But the sport fisherman, who traditionally has had the right to travel over the water surface in search of game fish, undoubtedly will question the legality of closing off navigable waters along the coast for the protection and convenience of the fish farmer. The pompano farmer also needs to anticipate problems in marketing, preserving and distributing his products. Iversen (1969) believes that the lack of trained personnel has also hindered progress in mariculture.

Among other species of fish receiving increasing attention as the object of mariculture is the salmon. In the State of Washington, early attempts at salmon farming in the 1950's were unsuccessful as problems with high temperatures, oxygen deficiency, disease, and inadequate food supplies all contributed to the failure to culture salmon in salt water enclosures (Anon., 1970). Recently, however, scientists from the National Marine Fisheries Service headed by Dr. Tim Joyner of the Biological Laboratory at Seattle, Washington, and from Oregon State University under the leadership of Dr. William J. McNeil, have produced evidence that salmonid fishes can be acclimated to salt water culture. Research at Oregon State University has shown that fry of selected races of most species of Pacific salmon can be acclimated to salt or brackish water. National Marine Fisheries Service scientists have successfully reared coho salmon, *Oncorhynchus kisutch*, in net enclosures floating in Puget Sound, where the fish grew from 0.7 to 10 oz (19.8 to 283.5 g) in less than 6 months. The results of feeding tests showed that conversion of food to flesh was very efficient: 1.5 lb (680.4 g) of wet pelleted feed produced 1 lb (453.6 g) of fish. The success of this rearing experiment was attributed to the use of floating pens moored in water with a significant tidal flow. The water, stable in temperature and rich in oxygen due to constant mixing, flowed in volumes large enough to carry away waste products and to help reduce transmission of disease.

As outlined by Drs. Joyner and McNeil, the way to a potentially profitable salmon culture operation would be to transfer hatchery-reared fry to nurseries where they can acclimate to salt water, rear them to fingerling size, and then transplant them to floating pens in coastal areas for rearing to a marketable size of about 8-12 oz (226.8-340.2 g). Taste tests have revealed that 10-oz (283.5-g), pen-reared coho are an excellent product, and, in the opinion of those who have tasted them, the flesh is superior to that of rainbow trout.

Bardach (1968b), who summarized information on fish culture experiments at La Jolla, California, reported that more than 20 species of marine fish have been reared from egg through metamorphosis to the adult form. Research on marine fish culture at La Jolla concentrated on the problems of rearing pelagic fish larvae in confinement and supplying large quantities of food. Studying the biology of very small, transparent larvae was also an important phase of the investigation. Success in developing the techniques of mass rearing has resulted in culturing many thousands of Pacific mackerel, *Pneumatophorus diego*, sardine, *Sardinops caerulea* and anchovy, *Engraulis mordax*.

During the experiments at La Jolla, one major problem—that of feeding—was overcome by the development of a technique for supplying very small food organisms at the time of complete yolk absorption (Bardach, 1968b). Food was supplied in large quantities so that larvae of low mobility could find food in all parts of the aquarium. Sardine larvae, for example, searched about 0.06 cubic inch (1 cc) of water per hour at the onset of feeding and required a minimum of 4 food organisms/hr to survive. As the larvae grew, larger particles of food consisting of copepods were required; the scientists collected the copepods, which gathered at night around a 1 000-watt underwater lamp. After the larvae were large enough to consume zooplankters larger than 0.01 inch (0.25 mm), supplemental feeding of *A. salina* was started.

The experiments at La Jolla also showed that the quantity of food present in the environment plays a subordinate role in larval growth rates; rather, it is the individual and species genetic potentials, which are in turn moderated by water temperatures, that are of primary importance (Bardach, 1968b). Bardach also pointed out that a slight increase in larval size is correlated with an increase in size of food particles eaten and in the ability to move farther per minute of swimming in search of food; hence, efficiency of living increases with size. Sardine-like larvae required about 30 days from onset of feeding to metamorphose to the adult form, whereas mackerel-type larvae metamorphosed to the adult form about 7 days after onset of feeding.

In one experiment involving 4 000 fry, it was found that at the onset of omnivorous feeding, Pacific mackerel larvae eliminated all other slower growing species, and within 9 days after hatching there was only a 50 per cent survival as a result of intraspecific predation (Bardach, 1968b). Problems of a nonbiological nature further reduced the remaining 2 000 fry to about 400 fish after 3 months. Six months after hatching, supersaturation of air in the sea water killed all but a few fish. Length and weight of 341 dead fish averaged 7.9 inches (200 mm) and 3.9 oz (110 g). On this basis, it was estimated that the yield would have been 0.6 lb/ft^3 (3 kg/m^2) of water or a projected 14 short tons/acre (31 metric tons/ha) at a minimum.

There are a number of other species of fish that have been mentioned by Iversen and Berry (1969) as suitable for farming, such as the Atlantic permit, *Trachinotus falcatus*, spotted seatrout, *Cynoscion nebulosus*, red drum, *Sciaenops ocellata*, red snapper, *Lutjanus aya* or *L. blackfordi*, grey snapper, *L. griseus*, and summer flounder, *Paralichthys dentatus*. Considerable interest is also being shown in mullet, *Mugil cephalus*, as a species suitable for mariculture in the United States, although there are a number of obstacles to be overcome. Iversen (1968) stated that the biggest disadvantage to farming this species is the very low market value in many areas of the United States, excepting Hawaii. Other problems associated with mullet culture are the high cost of collecting the young at sea in order to stock the fishponds and the sorting that is necessary to control predators.

The Hawaiian pond culture of marine fishes, primarily mullet, milkfish, *Chanos chanos*, tenpounder, *Elops hawaiensis*, and bonefish, *Albula vulpes*, provided a substantial portion of the fish consumed in Hawaii in former years (Hiatt, 1947). But in recent years, the pond catch comprised only a small fraction of the total fish production, the result of a decline in the number of ponds now used for fish mariculture. In 1969, for example, only 19 988 lb (9 metric tons) of fish and crustaceans were produced in ponds, compared to the total marine catch of 9 708 146 lb (4 400 metric tons). According to the Hawaii Division of Fish and Game, there are presently only two ponds in commercial operation on the island of Oahu and three on the island of Molokai. Other species of marine fishes and crustaceans caught in the ponds include carangids, *Caranx* sp., mountain bass, *Kuhlia sandvicensis*, barracuda, *Sphyraena barracuda*, threadfin, *Polydactylus sexfilis*, white crab, *Portunus sanguinolentus*, red crab, *Podophthalmus vigil*, Samoan crab, *Scylla serrata* and shrimp, *Bithynis grandimanus*.

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