Aquaculture

Husbandry of aquatic animals can contribute increasingly to supplies of high-grade protein food.

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Optimistic forecasters of the world food supply in the year 2000 predict that serious regional food shortages will exist; pessimists warn of widespread famine as populations in many countries increase more rapidly than agricultural production. The one bright spot in this otherwise gloomy picture is the rate of growth of 8 percent per year of the world fish harvest during the last decade (*1*). The annual harvest now amounts to 53 million metric tons (*2*) and is expected to increase for some time to come, though estimates of the possible total sustained yield differ widely, ranging from 120 to 2000 million metric tons. All are based on extrapolations from scanty data on primary productivity throughout the world's seas and on incomplete knowledge of the food relations of many harvested organisms.

Aquatic harvests supply almost nothing but proteins, since the bulk of aquatic plants are plankton algae that are uneconomical to harvest (*4*) and hold no promise for furnishing carbohydrate staples. A breakdown of the total yield from aquatic ecosystems into marine, fresh, and brackish water moieties shows that the yields from fresh and brackish water make up about 14 percent of the tonnage (*2*). Much of man's fishing has been in estuaries and bays of the sea, and in ponds, lakes, reservoirs, and streams, where he has long practiced aquaculture (*5*).

Aquaculture resembles agriculture rather than fisheries in that it does not rely on a common property resource but presumes ownership or leased rights to such bases of production as ponds or portions of, or sites in, bays or other large bodies of water. Products of aquaculture must compete successfully with those of fisheries and of animal husbandry; in Western food economy, aquaculture products such as trout, oysters, and shrimp bring good returns because they fall in the luxury class, whereas in developing countries various kinds of raised fish command a high price (*6*), since animal protein, including that derived from marine catches, is generally scarce. Although subsidized small home or village ponds may be justified in certain underdeveloped areas to help alleviate malnutrition, aquaculture, wherever it is practiced, should be examined primarily as a commercial enterprise that must compete with other protein supplies to be successful.

The organisms now being raised in aquaculture comprise several bivalve mollusks (mainly oysters of the genera *Ostrea* and *Crassostrea*), a few crustaceans (predominantly shrimp, in particular *Peneus japonicus*), and a limited number of fish species (*6*). Among the fish species, the carp, *Cyprinus carpio*, and selected other members of the same family, Cyprinidae (minnows), are the most important. Trout and salmon are also important in aquaculture, especially the rainbow trout, *Salmo gairdneri*, as are the Southeast Asian milkfish (*Chanos chanos*), and mullets, especially *Mugil cephalus*, and yellowtail (*Seriola quinqueradiata*), in Japan. Also noteworthy are the channel catfish industry (*Ictalurus punctatus*) in the southern United States and the use of *Tilapia* as pondfish, mainly in Africa (*6*). Most of these species are adjusted to life in fresh or brackish water, but the culturing of some marine fishes is being attempted, notably in Great Britain with plaice (*Pleuronectes platessa*) and sole (*Solea solea*) (*7*) and with pelagic (high seas) schooling species in Japan and the United States, among them the Pacific sardine and mackerel (*Sardinops caerula*, *Pneumatophorus diego*) (*8*) and the pompano (*Trachinotus carolinus*) (*9*). Some attached algae are also produced under semi-cultivation, both in temperate and tropical waters and certain phytoplankton species are cultured as food for oyster and shrimp larvae. These represent a special crop and are of minor or indirect nutritive value; they are omitted from this article, in which the potential of aquaculture for supplying high-quality protein is assessed.

Aquaculture furnishes the world with over 2 million metric tons, mainly fish. Mainland China alone reports annual production of 1.5 million metric tons of carp and carplike fishes (Fig. 1) (*6*). Two million metric tons represent nearly 4 percent of the total world catch and far exceed the United States, food fish harvest, although they are produced from a fraction of 1 percent of the world's waters.

Aquaculture ranges in intensity from simple weeding of natural stands of algae to complete husbandry of domesticated fish like trout or carp. It is sometimes difficult to distinguish intensive management from culture. The term, as used here, comprises practices that subject organisms to at least one, and usually more than one, manipulation before harvest. In addition, as in agriculture, the harvest in aquaculture takes most, if not all, the organisms tended. Most often only one species is raised, although a few to several compatible species may be cultured simultaneously.

To be productive for husbandry, aquatic animals should have the following characteristics. (i) They should reproduce in captivity or semi-confinement (for example, trout) to make selective breeding possible or yield easily to manipulations that result in the production of their offspring (for example, carp). Failing ease of breeding, their larvae or young should be easily available for gathering (for example, oysters). (ii) Their eggs or larvae or both should be fairly hardy and capable of being hatched or reared under controlled conditions. (iii) The larvae or young should have food habits that can be satisfied by operations to increase their natural foods, or they should be able to take extraneous feeds from their early stages. (iv) They should gain weight fast and nourish themselves entirely or in part from abundantly available food that can be supplied cheaply, or that can be readily produced or increased in the area where the cultured species lives.

Few aquatic organisms have all these attributes, and substantial expansion of

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the aquacultural crop depends in part on how biological and engineering skills can make the missing characteristics less crucial; other constraints are economic. I discuss here several operations and problems common to the raising of aquatic organisms (*10*), and I attempt to appraise realistically the potential of aquaculture on a world scale.

Selective Breeding of Aquatic Stock

Even before Jacob tended Laban's flocks, livestock had been subjected by man to selection for one or another desirable attribute, and breeding of domestic birds and animals has produced spectacular results. The first treatise on fish culture was written in China by Fan Li in 475 B.C. (*11*), but there are still only two aquatic animals over which genetic control has been exercised. These are carp and several species of trout; trout has a shorter and less varied history of breeding than carp. No true breeding programs exist with invertebrates, though oyster culture is advancing so rapidly that experiments in oyster genetics are likely to begin soon.

The breeding of aquatic animals, compared with terrestrial animals, has peculiar problems. Spawning habits often make the isolation of pairs difficult; isolation of numerous offspring requires many replicate ponds (aquariums are too unlike nature); and there is rarely more than one mating a year. Moreover, the environment has an overriding influence on the growth of poikilothermous animals; consequently, many different-sized animals of the same age are found together. Many aquatic animals require special environmental or social conditions for mating and reproduction, which are not easily duplicated under human control. Manipulations of water temperature or flow have triggered spawning; however, the development during the last two decades of the practice of hypophyzation, or treatment with pituitary hormone (*12*), to make some fishes spawn helps alleviate contraints on breeding for some species. This practice has influenced fish culture all over the world, from catfish growers in the southern United States and sturgeon breeders in the Ukraine, to the fishpond cooperatives of mainland China, where it is of paramount importance in making common carp produce eggs three times a year and in facilitating the propagation of its cyprinid pond mates, whose eggs were difficult

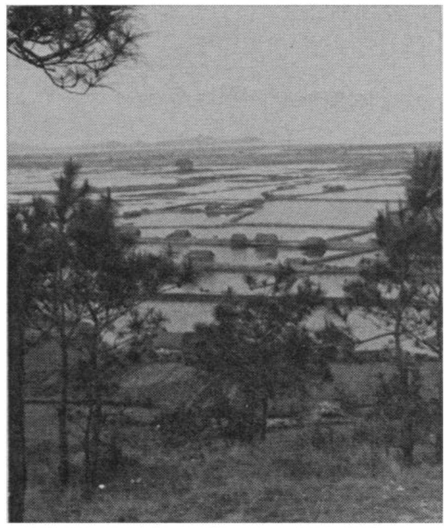

Fig. 1. Fishponds in Kwan Tung Province, China (F. Anderegg, photo).

to collect in rivers before the process of hypophyzation was developed. Use of pituitary material may also produce advances with the breeding of two species of fish important in brackish water culture—the milkfish and the gray mullet. Aquatic animals have one advantage over terrestrial animals from the breeder's point of view—a pair have large numbers of offspring, which permit mass selection.

Carp are readily adaptable to selective breeding because their eggs are large for fish eggs; they are not too delicate; and they are easily secured. Carp have been bred for fast growth, a body shape with more flesh than is found on the wild type, reduction of scale cover for greater ease in preparing the fish for the table, resistance to disease, and resistance to crowding and to low temperature (*13*). With such breeding practices as progeny testing (selection of parents according to the performance of their offspring) and diallele analysis (a system of mating that determines separately the genotypes of each parent) (*14*), further improvements on already well-domesticated strains may be expected. It is necessary to prevent reversions to the wild type. That these can occur rapidly is illustrated by the fate of carp introduced to America. After being brought to the New World in 1877 (*15*), carp was allowed to escape into lakes and rivers where indiscriminate mixtures of its prolific stock resulted in bony and scaly fish which soon became a nuisance in waters used for game fishing. There was no incentive for carp culture in the United States, where protein was abundant from land livestock. However, since carp has become a prized angling trophy in Western Europe, and because of the rapid eutrophication of American lakes and rivers (a process which favors carp) and the predicted narrowing of the gap, even in America, between the supply of terrestrial protein and the demand, it is not farfetched to think that carp may be cultured in the United States.

Trout, at least in America, were until recently raised mostly for stream stocking; consequently, disease resistance was the main concern in hatcheries not equipped for experiments in fish genetics. Demonstration of what may reside in the trout's gene pool has come mainly from two sources: the Danish table trout industry (*16*) and the experimental trout and salmon breeding program of the University of Washington in Seattle (*17*), where specially fed rainbow trout stock, continuously graded by selection during 30 years, grows to as much as 3 kilograms in 18 months while a wild rainbow trout in a lake at that age rarely weighs 200 grams (Fig. 2) (*18*); these fish tolerate higher temperatures than their wild congeners.

Trout and salmon eggs are larger than those of the carp; they develop slowly and are hardy, combining several advantageous properties. Salmon permit the establishment of hatcheries on suitable streams because they return to spawn to the stream with the odor of which they were imprinted as fry. In such hatcheries inadvertent selection from the spawning run of the largest—fastest growing—brood fish has produced strains that returned to the hatchery 1 year earlier than the offspring of their wild congeners. Salmonid fishes can be selected for higher fecundity, larger egg size, and better survival and faster growth of fry, and for exact timing of their return to the parent stream (*19*). These breeding potentials should be used to increase the abundance of salmon especially since improved techniques now feasible in United States salmon hatcheries could produce about ten times as many young fish as are now released (*20*).

Salmon-fishing regulations are still based on propagation potentials in natural streams and require that 50 percent of the run be allowed to escape the fishery. Salmon runs will increasingly depend on hatcheries that program their fish to return for stripping and the raising of a well-protected progeny whose rate of survival at the time of release is many times greater than that attained in nature, where maximum fish

Fig. 2. Wild and mass-selected, hatchery-fed rainbow trout, at the University of Washington School of Fisheries, Seattle. Fish are 2 years old, and the large one is the result of over 30 years of selective breeding. Their respective lengths can be estimated from the diameter of the bucket base, which is 22 centimeters.

mortality takes place during the first few months of life. Thus, the salmon harvest of certain river mouths may almost be doubled in view of the fact that hatchery-dependent runs need only a few fish to supply the next generation. Salmon are highly valuable fish [$65 million for the United States catch in 1965 (*21*)], and it may be worthwhile to press for regional revision of escapement regulations and to examine the economic requirements and consequences of hatchery improvements.

Another advantage of breeding fishes is the ease with which many of them hybridize (*22*). At the University of Washington at Seattle, male steelhead (that is, seagoing rainbow) trout were crossed with fast-growing freshwater rainbow females. The growth rate of the offspring was intermediate between that of the parents, their shape was more fusiform than that of the female, and they migrated to sea. They had a voracious appetite and adopted parent streams to which they returned as 2-year-olds, weighing 2 to 3 kilograms on the average and occasionally as much as 5 kilograms (*23*). They would probably not breed true in the second generation, and they should therefore be hatchery-produced, but they represent an interesting use of the sea's unused fish food.

Difficult as it may be to raise the progeny of one pair of parents of carp and trout, to do so with oysters is still more complicated. Mass spawning is usually done on oyster beds, and although the female of the genus *Crassostrea*, to which the American oyster belongs, retains the eggs inside her shells until after fertilization, paternity on the oyster bed is impossible to ascertain. Although there are thousands of eggs for each carp or trout, there can be up to 100 million for each female oyster (*24*). This fact, however, has aided in mass selection. Progressive growers of Long Island oysters raise the larvae in warmed water and use cultured algal food. They also give proper attention to stirring and other manipulations simulating planktonic conditions. The many eggs and improved survival of free-floating larvae permit a filter screen to be used to select only 20 percent of the largest, most rapidly growing early larvae. These larvae exhibit good growth throughout life (*6*). But to achieve true selective breeding, growers of Long Island oysters now plan to rear single oyster progeny; since oysters reverse their sex from male to female halfway through their adult lives, the possibility of freezing sperm from a functional male is being tested, and it may be possible to use it to fertilize the same oyster later when it becomes a female (*25*).

The Raising of Aquatic Larvae

Many aquatic animals go through larval stages which do not resemble their adult phase; some larvae, including those of shrimp or oysters, and of many fishes, are planktonic and minute and feed on the smallest organisms. More than with domestic birds or mammals, nursing them through their early lives poses difficult technical and nutritional problems to growers. In British experiments with raising plaice and sole larvae in captivity, as much as 66 percent survival through the stage of metamorphosis has been accomplished. Ultraviolet radiation of the water decreased the danger of bacterial infection; tanks without corners minimized encounters with solid obstacles; and salinity, temperature, and pH were controlled. The size of the first food offered was geared to the tiny mouthparts of the larvae, but was increased with their capacity to take larger live food. Nauplii of the barnacle (*Balanus balanoides*) were used at first; they were replaced by nauplii of the brine shrimp (*Artemia*) with subsequent admixtures of small oligochaetes (*Enchytrea*) when the small fishes had metamorphosed and were resting on the bottom. Finally, chopped mussels (*Mytilus*) were used. Since plaice larvae, just before settling, consume 200 brine shrimp nauplii per day, the production of several hundred thousand young plaice posed serious technical problems in continuous food culture (*7*).

Obtaining and correctly supplying food was a significant part of the experiments at the U.S. Bureau of Fisheries at La Jolla, California, with larvae of high seas schooling species such as Pacific sardines and mackerels. In these experiments very small food organisms had to be supplied at the precise time of complete yolk absorption, and in sufficient quantities to allow larvae of limited mobility to find food in all parts of the aquarium. Because sardine larvae search in only about 1 cubic centimeter of water per hour, at the onset of feeding, but require a minimum of four food organisms per hour to replace energy lost in swimming and body functions, the rearing of 2000 larvae in 1,800,000 cubic centimeters of water (500 gallons) meant replacing 7,200,000 food organisms removed by larval predation each hour or approximately 86,400,000 food organisms during a 12-hour day.

The large quantities of food organisms in varying sizes needed for these experiments were collected mostly at night. A 1000-watt underwater lamp connected to a submersible pump was suspended several feet below the surface of the sea. Copepods were attracted from a wide distance and concentrated near the pump where they were sucked up with water and transported to the surface. Plankton-enriched water was then passed through a series of filters, which further concentrated food organisms, and the highly enriched filtrate was piped to a 760 liter storage tank. Organisms with a cross-sectional diameter of 0.028 millimeter and larger were thereby collected. Before being fed to fish larvae, concentrated plankton was graded by filters to remove organisms larger than 0.1 millimeter. The portion containing large copepods, crab larvae, chaetognaths, and the like was fed to advanced fish fry and juveniles (*6, 8*) (cover photo).

Comparable techniques may help to achieve survival, after forced spawning in captivity, of milkfish and mullet. Inasmuch as these two species of economic importance in Asia are now raised from fry collected on the shores (Fig. 3) and as the fry are becoming scarce regionally, domestication of the two species, including manipulations ensuring high survival of fry will be an important advance for fish culture.

Although fish larvae are recognizable as fish even though they are not like the adults, invertebrates undergo more profound transformations from egg to adult. Oysters spend their first 2 weeks before they "set" as ciliated trochophores and veliger larvae needing flagellate algae for food. About 2000 cells of two or more species, for instance *Isochrysis galbana, Monochrysis lutheri,* and *Rhodomonas* and *Nannochloris* species, have to be available for each larva per day, and larger species are required to replace the smaller species as the larvae grow. Algae must be cultured en masse when oyster larvae are raised indoors, an innovation largely developed at the U.S. Bureau of Commercial Fisheries Biological Laboratory at Milford, Connecticut (*26*), and now expanded by progressive growers of Long Island oysters.

In shrimp raising, which is successful on a commercial scale only in Japan, there are problems with the larval stages before the animals can be fed chopped trashfish and shellfish. The operation, initiated by M. Fujinaga in 1934, begins in the spring with the collection of "berried" (egg carrying) females ready to release the stored spermatophores from their seminal receptacles; raising the water temperature speeds this and subsequent processes. After three distinctly different planktonic stages and 12 molts in about as many days, the postlarvae begin to crawl on the bottom; they still have to undergo some transformations and another 20 molts before they become adults. The early part of the life cycle of the cultured shrimp takes place indoors in ceramic tile-lined wooden tanks and in water heated to between 26° and 30°C. Diatom—mainly *Skeletonema costatum*—and flagellate cultures are maintained for feeding the early larvae, which are later given finely chopped mussel or clam flesh. When they have reached a length of between 15 and 20 millimeters or a weight of about 10 milligrams, they are stocked in outside ponds with arrangements for aeration and circulation (Fig. 4).

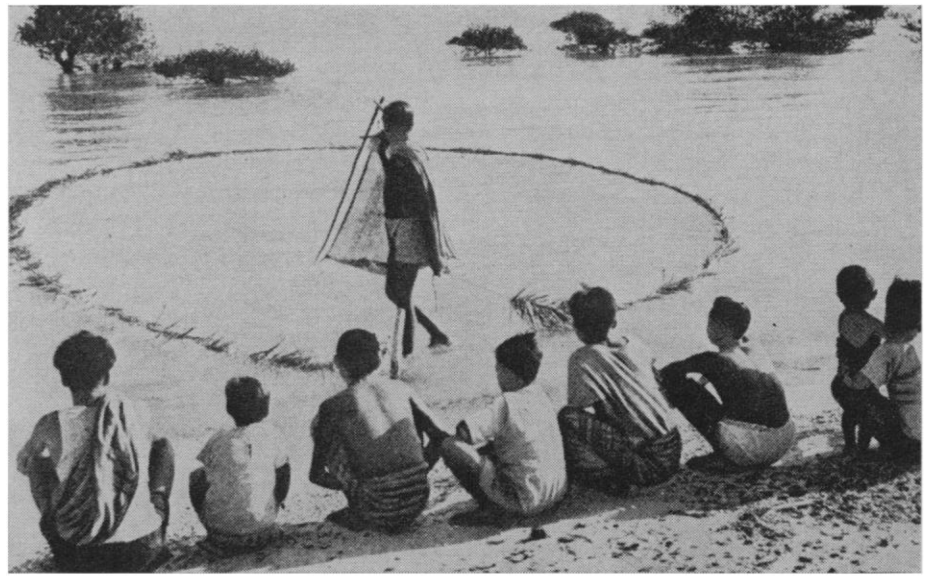

Fig. 3. Catching of milkfish fry on the coast of East Java (R. V. D. Sterling, photo).

In October or November, the shrimp, though not fully grown, are ready for market. They are about 10 centimeters long and weigh 20 grams having been fed once daily, converting 10 to 12 kilograms of food into 1 kilogram of shrimp. When the water later cools down to below 15°C, the animals no longer feed, but many of them may be retained without feeding for a later more favorable market (*6*).

The oldest shrimp-farming enterprise is now located near Takamatsu on Shikoku. It covers almost 10 hectares and has a staff of 30 men, including some in management research. Ten million shrimp were produced there in 1967, a quarter of which were raised to adult size; the rest were sold for stocking. The cost of production of cultured shrimp is certainly higher than that in any other aquacultural enterprise, but the wholesale price in Japan for tempura-sized shrimp of 6 to 10 centimeters is between $12 and $13 per kilogram, and the supply does not meet the demand. Shrimp farming of this type in a country whose material or labor costs are less favorable than those of Japan

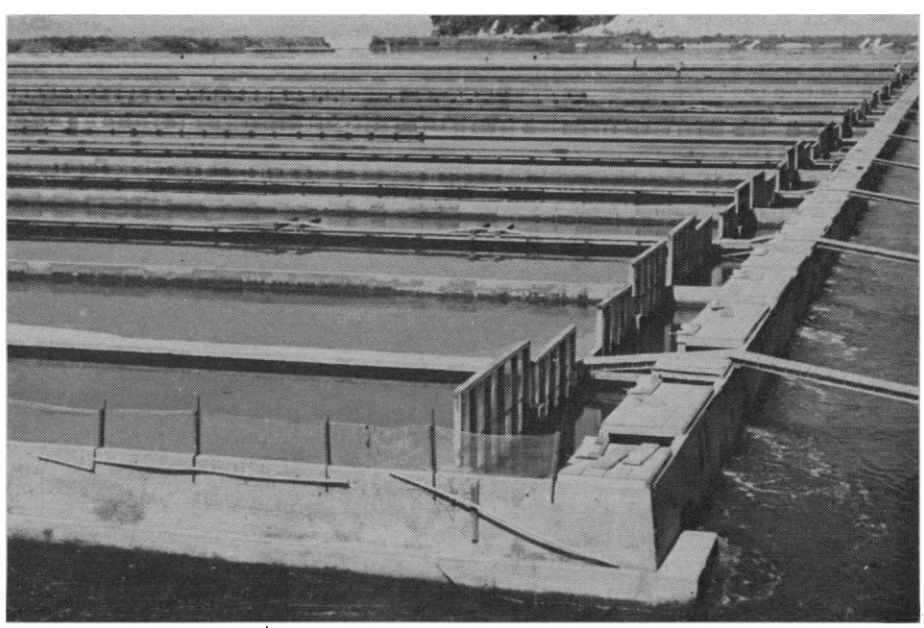

Fig. 4. The 28 running-water ponds (91 by 9.1 meters) for culturing adult shrimp at the Shrimp Farming Co., Takamatsu, Japan.

would not be possible (*6*). There are, however, opportunities for greater mechanization and for feeding innovations that will simplify the most laborious parts of culture operations for larval as well as postlarval shrimp. The use of the most improved shrimp-culturing methods with fast-growing species may hold some promise for a number of regions in the world (*27*).

Making Full Use of the Water

Aside from selecting the best suited strains, a practice not yet widely followed in aquatic husbandry, aquaculture should make use of the entire water column where possible and be three-dimensional, as it is in China and other Asian countries, where common carp is stocked with other species of the minnow family (Cyprinidae) such as the grass carp (*Ctenopharyngodon idella*), the silver carp (*Hypothalmichthys molitrix*), and the bighead carp (*Aristichthys nobilis*) (*28*). The success of this method is based on the different food habits of the respective species; the carp is a bottom feeder; the grass carp and the silver carp feed on plants (banana leaves, even) and beanmeal or rice bran supplied to them from outside the ponds; and the bighead carp uses the plankton surplus in the well-fertilized water. Thus, the various water layers and all potential food sources are used (*29*).

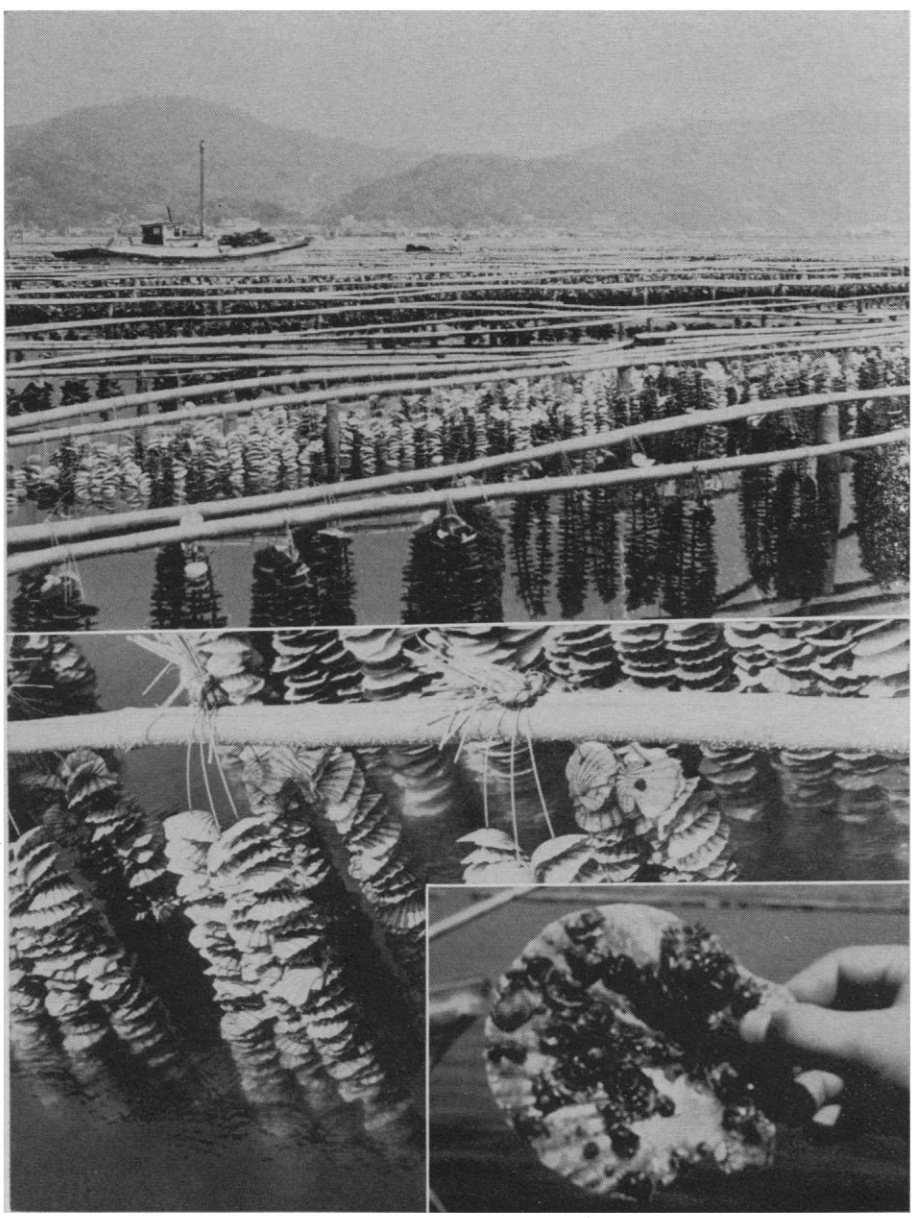

Fig. 5. Seed-oyster production near Hiroshima, Japan. (Top) general view of area; (bottom) detail of above; (bottom right) close-up of oysters on scallop shell, several weeks after setting (J. H. Ryther and author, photo).

The culture of oysters in Japan's best oyster-growing district, Hiroshima Bay, also is an illustration of the use of the entire water column (*6*). Seed oysters are collected on scallop shells suspended on wires from a bamboo framework driven into the bottom (Fig. 5). Biologists from the prefectural and municipal laboratories monitor the plankton during the spawning period and advise the growers on the best time for spat collection. It is not uncommon to collect several thousand spat per scallop shell, although the average is about 200. The shells are removed from the collecting frames after 1 month when the surviving oysters have reached a size of about 12 millimeters. They are then cleaned, culled, and restrung on heavier wires separated by bamboo (and more recently by plastic) spacers (Fig. 6). These wire rens are suspended from bamboo rafts, buoyed by floats of various kinds, and extend to a depth of 10 to 15 meters. Floats are added as the oysters grow, and before harvest require several times the support they needed at the beginning of the growing season. Long lines instead of rafts are an innovation in the method of suspension, but they are still only a variant on the hanging-culture technique, which uses the water column efficiently and which protects the oyster from its bottom-living predators, such as starfish and oyster drills.

A typical raft, about 20 by 25 meters carries 600 rens and produces more than 4 metric tons of shucked oyster meat per year (Fig. 7). On a per-hectare basis, this harvest amounts to 58 metric tons, if it is assumed that only one-fourth of a certain area of intensive cultivation is covered by rafts, as is the current practice. Such yields result from intensive care and high primary productivity in the water that is dependent on tidal exchange and fertile terrestrial runoff. By comparison, the average is 5 metric tons per hectare of well-managed, leased oyster ground in the United States and the peak harvest of 300 metric tons per hectare of mussels (*Mytilus edulis*) also grown with hanging culture in the bays of Galicia in Spain. On public oyster grounds in the United States, where the mollusks are a minimally managed common property resource, the average per hectare is only 10 kilograms (0.001 metric ton) or less (*6*).

Fertilization and Feeding

Fertilization of bays, fjords, or enclosures has led to increases in phyto- and zooplanktons, but favorable cost-benefit ratios for use with fish have not been proved (*30*). In ponds (including brackish ones) organic and inorganic fertilization has been efficacious. In Israel, fertilized carp ponds, some with admixtures of *Tilapia* and mullet, produce twice the tonnage per hectare of unfertilized ponds, and fertilization and additional feeding doubles the yield again (*31*). Fertilized *Tilapia* ponds in which the fish were also fed have yielded as much as ten times the crop of unenriched ones (*32*).

Many kinds of inorganic or organic fertilizers can be used, but sewage which produces dense invertebrate populations certainly works well. Munich sewage ponds with a slow exchange of water produce 500 kilograms of carp per hectare per year and a profit for their operator, the Bavarian Hydropower Company; the method requires large tracts of land, however; under temperate conditions rising land values threaten to make it obsolete (*6*).

In a much warmer, rapidly flowing stream in West Java, with a high sewage content, carp, confined in bamboo cages to graze on the dense carpet of worms and insect larvae in the sandy substrate, grow rapidly to yield 50 or more kilograms of fish per square meter of cage surface, or 500 metric tons per hectare (*33*). Even with allowances made for only partial use of the stream surfaces, this practice clearly represents an extremely efficient and ecologically sound use of sewage, especially in warm waters. The main drawbacks to this practice arise because the fish are not always well cooked before they are eaten.

In addition to the fertility of the water, its temperature, especially in a colder climate, is also very important. The most spectacular use of naturally warmed water for fish culture is in Idaho's Snake River valley trout-farming district, where springs of an even 16°C (optimum temperature for trout) gush forth from the canyon wall year in and year out. A thousand tons of trout can be raised in a year on every 2830 liters per second (100 cubic feet per second) that flow from these springs. Such unprecedented results in fish husbandry depend on high-density stocking, fast growth, mechanization, and cheap feed—the latter being locally procurable since the Snake River valley is also a stock feed-growing area (*34*). Most of all, however, the high yield depends on the flushing of growth-inhibiting wastes from the trout raceways. Hence, it is more appropriate to relate weight gain to water flow rather than to water surface or volume. By such a measurement, production would be around 170 kilograms per liter per second.

Fig. 6. Oyster raft culture in Hiroshima Bay, Japan; the scallop shells to which the growing oysters are attached are being spaced more widely as they are restrung, after cleaning.

Naturally warmed water is not prevalent, but man-made heated effluents occur with increasing frequency. In fact, thermal pollution may become a threat to some natural waters because it hastens eutrophication. Heated power plant effluents, however, can also be used to the advantage of the aquaculturist. At the atomic energy plant at Hunterston, Scotland, cooling water, ascertained to be nontoxic to fish, was fed into cement troughs for sole and plaice raising. Both species were grown to marketable sizes in 6 to 8 months at between 15° and 20°C, as compared with the 3 or 4 years needed for the same growth under natural conditions (*35*).

A progressive grower of Long Island shellfish used about 57,000 liters per minute of cooling water discharge of the Long Island Lighting Company. The cooling water is taken from a deep section of the bay and has a high nutrient content, which favors oyster growth as does its warmth. Year-round production in a near 3-hectare lagoon of both oysters and hard clams (*Mercenaria mercenaria*) has been achieved, and seed oyster production in the heated lagoon promises to be highly successful. Summer water temperatures above 30°C, first feared to arrest growth or to be lethal, in fact, promoted exceptionally rapid growth (*6, 25*). At the atomic plant at Turkey Point (Florida), replicate feeding trials by the University of Miami with shrimp (*Peneus duorarum*) and pompano (*Trachinotus carolinus*) are in progress to compare the effects of different levels of water temperature and consequently of different levels of heated water admixture (*9*). Heated waste water is also used for freshwater fish culture in the Soviet Union (*36*).

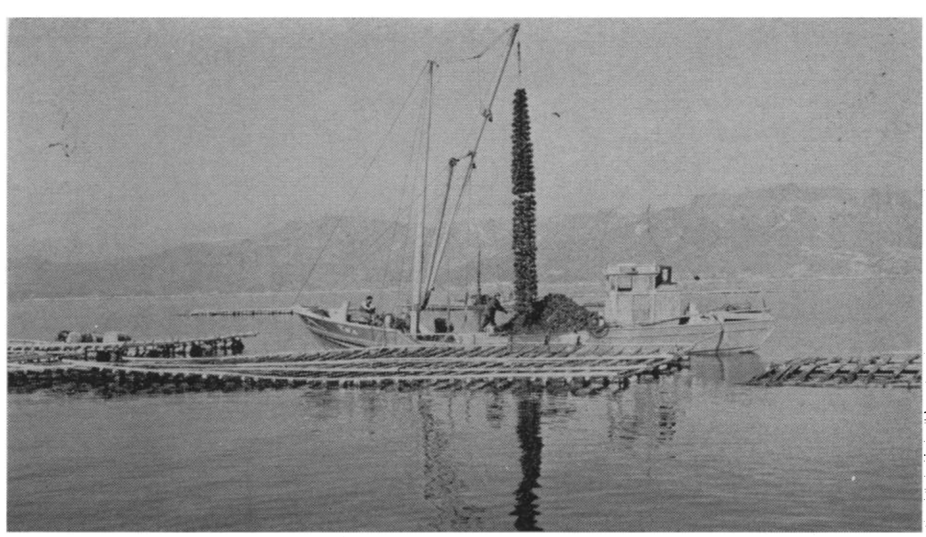

Fig. 7. Harvesting oysters in Hiroshima Bay, Japan. The rens of scallop shells with their attached oysters are strung from the boom (Japan Fish Agency, photo).

Status and Potential of Aquaculture

Aquaculture, practiced with a far wider range of species than mentioned here, is found in most of the world. In many areas it occurs at a subsistence level, and its potential contribution to the food supply has not been assessed (*37*). Village ponds, once a hopeful development in Africa, for instance, are now in disrepair and their potential is not being realized (*32*). Local fish ponds can be important, however, as has been demonstrated in Taiwan, mainland China, and Indonesia (*6*).

Husbandry of aquatic animals brings increasing financial returns as it is practiced on a larger scale. Culture intensities vary, as do the fixed and variable costs of the operations and the yields (Table 1). From a commercial point of view, the return on the investment is of most interest; in milkfish culture the annual return ranges from 10 to 20 percent or more, and increases with the intensity of cultivation. Malayan mixed pig and fish farms yield 30 percent, and similar returns are noted in the oyster business (*6*).

Aquaculture can be not only a lucrative business but it may even produce yields high compared with the harvest of comparably sized land surfaces. The relative scarcity of such peaks in aquacultural production, especially in the tropics, is caused by a lack of biotechnical engineering and managerial skills, the absence of suitable credit or seed capital for even low-cost installations, and the absence of transport and marketing facilities that might encourage the development of a product for a certain market, and so forth.

This is well illustrated by a comparison of Indonesian and Taiwanese milkfish culture in brackish water. Milkfish (Fig. 8) feed predominantly on bluegreen algae and are raised in pond complexes on land cleared of mangroves. Canals permit the control of water level and salinity by means of sluices, which regulate tidal or freshwater flow (*38*) (Fig. 9). Average Indonesian and Philippine annual harvests are 300 to 400 kilograms per hectare, whereas Taiwanese milkfish raisers attain nearly 2000 kilograms on the average, in spite of a cooler climate (*39*). Cooperatives, rural reconstruction agencies, a good layout of the farms, control of predators of the fry, some fertilization, and prevention of siltation of ponds and connecting water bodies are some of the secrets of successful milkfish farming in Taiwan. For similar reasons there occur in mollusk culture the aforementioned wide range of yields, from nearly 10 kilograms per hectare on public oyster grounds in the United States to the 58,000 kilograms per hectare in Hiroshima Bay.

Filter feeding mollusks and milkfish are brackish water plankton- or algae-feeders, respectively. These hold more promise for protein-deficient regions than do the carnivores of the same environment because it is more sound to increase the fertility of the water than to produce extraneous feed, let alone to raise one aquatic animal with scrap from another, which is perhaps already being used, or could be used, directly for human consumption.

Most products of aquaculture could be called luxury foods, whether they are sold as high-priced items in a food economy with wide consumer choice (for example, shrimp in Japan, trout in the United States) or boost the scant animal protein supply of developing nations (for example, milkfish in Southeast Asia), where they also bring a good return to the producer. It might seem unrealistic, therefore, to expect aquaculture to help alleviate the world protein deficiency, but such is not necessarily the case. Luxury foods stop being a luxury when they can be mass produced, a case well exemplified by the broiler chicken industry in the United States and Western Europe.

Differences in biology between chickens and aquatic animals notwithstanding, some of the latter could well become mass-produced cheap and abundant foods at conversion rates of two parts of dry feed to one part of fish flesh. Among fresh and brackish water fish, especially trout, carp, and catfish can be raised with pellets. Chinese carp and certain tilapias eat leaves and stems of leafy plants; other fish feed on algae. In Southeast Asia well over 200,000 hectares of ponds now lie in former mangrove areas; there are in the tropics vast unused mangrove regions, some of which could be turned into pond com-

Table 1. Selected ranges of aquaculturals yields (*6*) per year. Results are given in kilograms per hectare except as noted. The value is in dollars per hectare except as noted.

Type of cultivation	Location	Yield	Approximate wholesale value of annual crop
Oyster			
Common property resource (public grounds)	U.S.	9	38
Intensive cultivation, heated hatchery, larval feeding	U.S.	5,000	21,000
Intensive care, hanging culture	Japan*	58,000	67,000
Mussels			
Intensive care, hanging culture	Spain*	300,000	49,000
Shrimp			
Extensive, no fertilization, no feeding	S.E. Asia	1,000	1,200
Very intensive, complete feeding	Japan	6,000	43,000
Carp			
Fertilized ponds, sewage ponds	Israel	500	600
	S. Germany	500	
Fertilized ponds, accessory feeding	Israel	2,100	
Sewage streams, fast running	Indonesia*	125,000	
Recirculating water, intensive feeding	Japan	100†	114†
Catfish			
Ponds, no fertilization or feeding	Southern U.S.	200	70
With fertilization and feeding in slowly flowing water		3,400	2,400 (net profit 300)
Milkfish			
Brackish ponds, extensive management	Indonesia	400	
With fertilization and intensive care		2,000	600
Trout			
Cement raceways, intensive feeding, rapid flow	U.S.	170†	168†

*Values for raft culture and comparable intensive practices based on 25 percent of the area being occupied. † Per liter per second.

plexes for the culture of fish. Mollusk production, though limited eventually by the suitability of grounds, could be expanded, and above all intensified in the areas where it is now prevalent. Aquaculture is only beginning to develop such practices as manipulation of the temperature regime to achieve best growth, devising simple automated feeders that fish can learn to activate themselves, and building machines that simplify harvesting. Several disciplines are expected to contribute to the development of aquaculture. Since intensive husbandry alters the conditions of nature, a knowledge of the ecology of the cultured organisms in both natural and artificial states is essential. Engineering can also make increasingly important contributions to aquaculture development as it has in the successful pilot-scale raising of plaice and sole by the British Whitefish Authority (*40*). It was the basis for the as yet theoretical calculation that "the annual British catch of plaice could be housed in shallow ponds covering 1¼ square miles in extent" (*7*).

Japanese yellowtail fish are now raised at high density, and with sequential cropping have already achieved yields of 28 kilograms per square meter (280 metric tons per hectare) and shown that it is economical to use small portions of the sea under very intensive management. The success with this oceanic schooling species and the fact that other species of similar habits had become adapted to confinement led to the speculation that still others, such as tuna, might behave similarly and that their mass culture under controlled conditions might become possible. In fact, Inoue of the Fisheries Research Laboratory, Tokay University, Japan, urged that Japan take the initiative in launching a tuna-rearing project in the equatorial Pacific, where atolls and lagoons could be used as sea farms (*8*).

Such projections say nothing of the problems of translating small to modest enterprises into much vaster ones—the main one likely to be the procurement of many millions of tons of suitable food. Trashfish, in part now used for fish meal, krill and other marine organisms lower in the food chain than the highly prized fish to be cultured have been thought suitable, provided that they can be produced at a low enough cost. The theoretical potential of marine fish culture also rests on the assumption that marine fish can be induced to function sexually under artificial conditions, as have many freshwater fish.

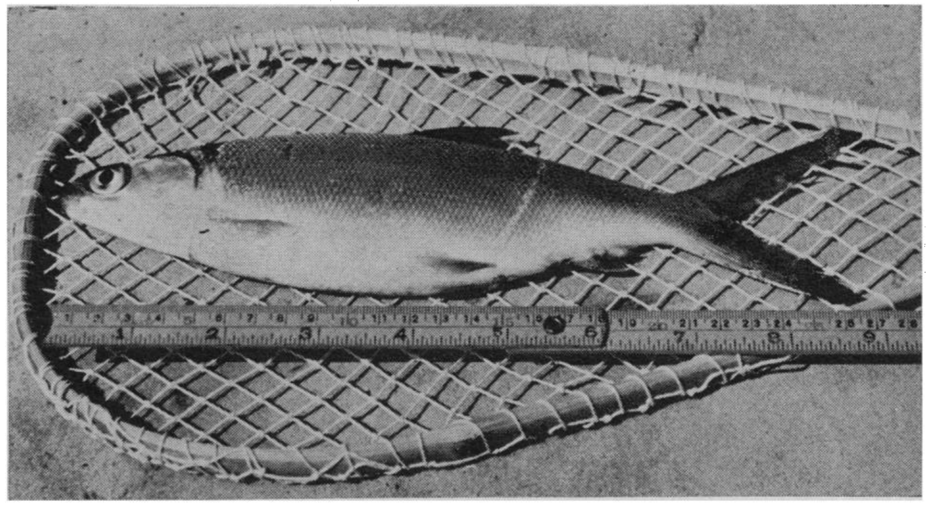

Fig. 8. The herbivorous brackish water milkfish of Southeast Asia; the specimen is about 6 months old (Department of Fisheries, Taiwan, photo).

Hormone stimulation is expected to be one of the solutions to this problem along with rearing an initial breeding stock born and adjusted to life in artificial environments.

But even without further advances through research, a considerable increase of aquacultural yields appears attainable soon by consistent application of already known techniques on inefficiently managed fresh and brackish water bodies. It has been advocated (*4*) that millions of hectares of ponds be constructed in Asia, Latin America, and Africa to help satisfy the protein needs of these areas. If local economic and socio-political constraints were removed, these new waters and the upgrading of presently existing ones could yield by the year 2000 a harvest of 30 to 40 million metric tons (*3, 41*) produced near areas of need, which are still likely to lack refrigeration.

Long-term and large-scale projections of yields attainable through practicing aquaculture with marine animals, outside the brackish water zone, can hardly be attempted; true mariculture is in its infancy. However, experiments in several locations have established that it is technically feasible, and no doubt the intensive development and success of brackish water aquaculture will lead to further efforts to develop mariculture on a large scale. It is too early, however, to tell where or under what conditions such efforts could become economically sound.

Fig. 9. Milkfish pond complexes near the coast of East Java (W. H. Schuster, photo).

Summary

The role of aquaculture in producing high-grade animal proteins for human nutrition is discussed. Raising and tending aquatic animals is mainly practiced in fresh and brackish waters although there are promising pilot experiments and a few commercial applications of true mariculture. Yields vary with the organisms under culture and the intensity of the husbanding care bestowed on them. The products are now mainly luxury foods, but there are some indications that upgrading of the frequently primitive culture methods now in use could lead to increasing yields per unit of effort and to reduced production costs per unit of weight. Under favorable conditions, production of animal flesh from a unit volume of water far exceeds that attained from a unit surface of ground. With high-density stocking of aquatic animals flushing is important, and flowing water or tidal exchange is essential. Combinations of biological and engineering skills are necessary for full exploitation of aquacultural potentials; these are only partially realized because economic incentives may be lacking to tend aquatic organisms rather than to secure them from wild stocks, because of social, cultural, and political constraints. Nevertheless, a substantial development of aquaculture should occur in the next three decades and with it a severalfold increase in total yield.

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