a risky activity but very profitable in economic terms.

Conclusions

Traditional mollusk culture maintains its position but is encountering problems of limited availability of water. Transfer out to the open sea which is less polluted has been piloted in Languedoc (France) for two decades, but has demonstrated neither the suitability of the techniques nor their profitability, and production has stagnated.

The explosive growth of the production of marine fish in cages can be said to demonstrate the true revolution in Mediterranean mariculture. This is based entirely on species with a high commercial value. This type of rearing has expanded eastwards from the European Mediterranean countries but has not yet reached the southern shore.

Markets, particularly the huge European market of 360 million inhabitants, are not yet saturated. Diversification of the species produced may open up new markets. The expansion of cage-based mariculture has not yet finished, while progress in technology is unpredictable.

The major missing element in Mediterranean aquaculture is the rearing of penaeids, in spite of several sporadic but insignificant attempts at production in Southern Italy and Morocco.

See also

Mariculture Overview. Salmonid Farming.

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MARICULTURE OVERVIEW

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Introduction

Mariculture has been defined as the cultivation, management, and harvesting of marine organisms in their natural environment (including estuarine, brackish, coastal, and offshore waters) or in enclosures such as pens, tanks, or channels. The range of organisms cultured includes seaweeds, mollusks, crustaceans, fish and, a more recent development, echinoderms. As with all forms of aquaculture, operations range from extensive to highly intensive. At one extreme, extensive mariculture is simply based on the protection of the stock to improve survival rates of wild juveniles, with few or no nutrients supplied; at the other extreme, intensive mariculture may take place in an enclosed system where all nutrients are provided by the farmer and the environment is maintained through water filtration, sterilization and oxygenation, and the control of light and temperature regimes. Other forms of mariculture include ranching, in which juveniles (notably crustaceans and salmonids) produced in a hatchery are released into the marine environment where they feed and grow in the same way as their wild equivalents. Low survival rates in ranching are set against the reduced costs in comparison with those of a full-scale farming operation.

In this article the worldwide history of mariculture is reviewed, followed by a summary of its current status and opportunities and constraints for future development. More detailed information relating to major species groups (e.g., salmonids, marine fish, crustaceans, and bivalve mollusks) can be found in other articles, as can details of environmental impacts, fish health, and social and economic aspects of mariculture.

History

The beginnings of aquaculture can be traced back over 4000 years; evidence of the culture of carp, tilapia, and other freshwater fish are found from Egypt and China. An Egyptian bas-relief dated 2500 BC appears to show pond rearing of tilapia, while in China the works of Fan Li (500 BC) clearly demonstrate that carp farming was a well-established and profitable occupation. The techniques of carp rearing spread west from China and became established throughout Europe in the Middle Ages, being associated with the provision of fish for the monasteries to supply the needs of the religious calendar.

Records of mariculture can be found dating back around 2000 years; in Europe the Greeks and Romans were familiar with extensive oyster farming. This was based on the protection of juveniles (spat) that had settled in the intertidal zone. Similar progress was being made with oysters in Japan. The first marine fish culture probably began around this time. The juveniles of many valued species of marine fish (e.g., mullet, sea bass, and eels) naturally ascend estuaries and enter brackish lagoons. Culture was (and still is in the valley of the Po delta and the salt marshes of the Arcachon basin of the French Atlantic coast) based on preventing the return seaward migration of part-grown fish by erecting barriers and constructing ponds and enclosures. In the east (Indonesia, Philippines, Taiwan) such methods have been in use for 600 years, based on euryhaline species such as milkfish (*Chanos chanos*). Coastal dykes have been constructed to enclose pools of brackish water known as tambaks. Cage culture may have originated in South-East Asia around 200 years ago; in Cambodia such structures were utilized to hold and feed captured wild fish until they reached market size. The basic cage structure remains the same, consisting of a support and flotation collar providing a framework for a net bag of appropriate mesh size to allow water to circulate but retain the smallest fish and a mooring system.

All of these forms of mariculture rely on the collection of juveniles or part-grown animals that are the result of natural spawning in the wild. Although simple, low-technology, and low-cost, such methods have major disadvantages, including the following.

- Uncertainty of the success of collection – year to year variations are associated with spawning and recruitment success and weather and ocean conditions.
- Limitations on numbers available for mariculture without affecting natural stocks. Declines in numbers of eels and milkfish have been ascribed to excessive removal of juveniles for farming.
- Variations in quality – age, size, disease, parasites.
- Variations in species – nontarget species may be captured and killed or discarded in large numbers.
- Seasonal availability – natural spawning in temperate and subtropical waters tends to be an annual event; juveniles are only available for a few days or weeks each year. This leads to poor use of ongrowing facilities and a glut when individuals reach market size. The availability of marketable stock may not coincide with the time of highest demand.

The disadvantages of collection of stock from the wild led to the major development that made intensive aquaculture possible: controlled reproduction in an enclosed environment. Parental stock (including seaweeds) is maintained in conditions where it reproduces either naturally or after the application of physical stimulation (change of light, temperature), hormonal treatment, or mechanical pressure (salmonids). Thus the whole life cycle can be controlled. One of the first records of captive breeding is that of brown trout by a French monk, Dom Pinchot, in the fourteenth century. Techniques for salmonid breeding and rearing developed mainly with the aim of augmenting wild stocks, often for sporting purposes; in the nineteenth century trout eggs were transported around the globe and self-sustaining populations have become established on all continents except for Antarctica. Salmonids have the advantage of producing large eggs (several millimeters diameter, compared with 1 mm for most sea fish) that hatch into large alevins, able to ingest food such as liver paste or dry crumb diet at first feeding. True marine species of fish, crustaceans, and mollusks are much more difficult to hatch and wean; their tiny size and pelagic behavior still provide a challenge for mariculturists. Modern hatcheries for marine species such as sea bass, sea bream, clams, and shrimp incorporate complex facilities for producing live feeds (microalgae, rotifers, copepods) to feed juveniles to the stage when they can be transferred to the growout zone (mollusks) or fed with artificial diets (fish and crustaceans).

Intensive production of juveniles in such hatcheries is inevitably an expensive, technologically demanding process. However, benefits generally outweigh the risks attached to the harvest of juveniles from the wild as reviewed above.

Modern mariculture, to a greater degree than culture in fresh waters, is market-driven. Traditional freshwater culture, as practiced with the polyculture of different species of carp in China, is aimed at exploiting local resources to supplement the protein in the diet of local people. Marine species are selected for their market potential, locally or for export, and for some countries mariculture has become a significant generator of foreign currency, notable examples being penaeid shrimps in South-East Asia and salmon in Chile.

The selection of species for commercial culture in a particular location should take into account the following factors:

- The likelihood of marketing at a profit after all production, processing, and transport costs have been taken into account.
- Ability to satisfy a market: Once a market has been established, supply must be maintained.
- Suitability of the species for culture throughout the whole life cycle; this includes management of broodstock, eggs, juveniles, and adults. If this is possible, natural stocks need not be collected, once the initial stock has been established in culture.
- Aspects of the biology such as growth rate, age at which sexual maturity is first reached, and time taken to reach market size. It is important that individuals meeting the size and quality standards required by the market are available constantly or at the appropriate times of year.
- Whether it is necessary to import 'exotic' species or whether a local species fulfills these requirements. Southern Hemisphere countries, notably Chile but also Australia and New Zealand, have established major mariculture industries based on the farming of Atlantic and Pacific salmon, natives of the Northern Hemisphere.
- Local technologies and skills. Local fishermen are well suited to operating coastal farms but in developing countries the skills required to operate the technologically complex hatcheries for marine fish may have to be taught.
- Similarly, in order to establish a mariculture operation, feed, equipment and processing facilities should be available locally.

Above all, quality, availability, and delivery must be guaranteed. Aquaculture products compete on the market with other commercially traded food products and such guarantees can place them at an advantage over fish or shellfish captured in commercial fisheries. In Japan, the quality of farmed yellowtail (*Seriola quinqueradiata*) is now preferred to that of wild.

Table 1 Worldwide aquaculture production from different environments: 1988, 1992, 1997

	Production (t)		
	1988	*1992*	*1997*
Overall	11 700 230	15 477 350	28 808 414
Fresh water	6 774 907	8 932 836	17 043 616
Brackish water	1 048 687	1 387 164	1 613 412
Marine	3 876 636	5 157 350	10 151 386

Current Status of the Mariculture Industry Worldwide

Figures produced annually by FAO demonstrate worldwide growth in the production of all groups of species cultured in marine and brackish waters. **Table 1**, based on FAO data, demonstrates growth between 1988 and 1997, a time during which annual capture fishery output has remained relatively static at around 80 000 000 tonnes.

Brief Review of the Mariculture of Selected Species

The examples below have been chosen to give an indication of the growth in production (or otherwise) of some of the most important groups of cultured marine organisms, with brief notes on culture methods and significant features of the industry.

Seaweeds

Macroalgae, commonly referred to as seaweeds, are cultured almost exclusively in the far east, where they are harvested for culinary use or for processing to extract agar, carrageenin, alginate, iodine, or pharmaceuticals. Three major species groups are farmed:

- Red seaweeds (Rhodophyceae), mainly of the genus *Porphyra*, known as nori in Japan and laver in Britain. Overall production of red seaweeds in 1997 was over 175 000 t, mainly from Indonesia, China, Japan, Korea, and the Philippines. Preparation of harvested fronds for the table market is a specialized process involving desiccation, shredding, and compressing into thin, translucent sheets. Production of another genus, *Gracilaria*, is increasing; overall output for 1997 was 133 500 t, over 100 000 t of which came from Chile.
- Brown seaweeds or kelps (Phaeophyceae), mainly *Laminaria* and *Undaria* species, make up the

largest group with an annual production in 1997 of almost half a million tonnes. Mainland China is easily the major producer with almost 400 000 t harvested: other major producers are the Korean Republic and Japan.
- Green seaweeds (Chlorophyceae) are produced in Japan, Korea, and the Philippines, the overall quantity (1997 production 33 000 t) being far lower than those of the other groups.

Seaweeds are generally cultured in floating or fixed 'fields' installed according to regulations designed to prevent the build-up of silt and to allow navigation. There is increasing interest in incorporating seaweed culture into polyculture systems; in China seaweeds are grown together with scallops and abalone.

Mollusks

The earliest recorded mariculture was based on the protection of oyster and mussel beds 2000 years ago and these bivalves still provide the bulk of mollusk production worldwide. Filter-feeding bivalve mollusks such as oysters, mussels, scallops, and clams present two major advantages for the farmer; they feed entirely on natural production (mainly phytoplankton) and are either attached to a substrate or move only short distances. Thus feeding costs are confined to the hatchery (if used) and containment costs are low. Of the other mollusks, abalone (*Haliotis* spp.) culture is developing in many tropical and subtropical countries (overall production < 5000 t) nd preliminary trials of cephalopod rearing are ongoing.

The farmed oysters belong to the genus *Ostrea*, which includes the European flat oyster *Ostrea edulis* and *Crassostrea*, including the Pacific (cupped oyster) *Crassostrea gigas* and the American oyster *Crassostrea virginica*. Production of the European oyster is in decline (9000 t in 1988; 6500 t in 1997) with considerable year-to-year variation. Disease and slow growth relative to the Pacific oyster have failed to compensate for the higher prices achieved. Over the same period, production of the Pacific oyster has increased from over 1 200 000 t to 3 000 000 t, over 2 300 000 t of which come from mainland China. Production in Europe greatly exceeds that of the native oyster; in France around 2000 t of native oyster and 150 000 t of Pacific oyster were produced in 1997.

Oysters may be cultured on the seabed in shallow water and in the intertidal zone, in mesh bags supported on trestles or suspended on ropes within the photic zone where phytoplankton are abundant. As with all mollusks, water quality is important and standards restricting bacterial contamination are enforced to protect human health.

Almost all species of cultured mussels belong to the genus *Mytilus*. These are cultured along the coasts of Europe, the Far East, India, and North and South America. Culture methods range from the protection of stocks growing on the seabed, to ropes attached to posts (bouchots) driven into the seabed in the intertidal zone, to ropes suspended from rafts. This last method has been used effectively in the highly productive rias of Gallicia, northern Spain where annual production is around 200 000 t. Overall world production of mussels is around 1 000 000 t each year and remains fairly steady, with increases in some countries being balanced by decreases in others.

Shrimps

Penaeid shrimps are cultured throughout coastal regions of South and South-East Asia and South America. Much of the culture takes place in large excavated ponds with tidal water exchange. Hatchery techniques were developed for the Kuruma shrimp *Penaeus japonicus* over 50 years ago to provide juveniles for restocking the Sea of Japan. However, in other countries production has until recently largely depended on the collection of wild postlarvae. A strong market and high prices in developed countries have encouraged rapid development of shrimp culture, often resulting in environmental damage such as destruction of mangroves, siltation and blocking of channels in estuaries and requiring dependence on antibiotics to counteract diseases associated with poor environmental conditions. In some countries a combination of these factors has resulted in a crash in production, a notable example being that of *Penaeus monodon*, the giant tiger shrimp in Taiwan (1988 output 30 000 t; 1997 output 5000 t). Over this period total annual production of *Penaeus monodon* grew from 200 000 t to 500 000 t with major increases in countries such as Thailand (40 000 t in 1988; 210 000 t in 1997) and India (44 000 t in 1988; 100 000 t in 1997). Production of the whiteleg shrimp, *Penaeus vannemi* grew from 67 000 t to 170 000 t, most of this being around the coasts and estuaries of Ecuador.

Fish

Salmonids All salmonids spawn in fresh water, but many species are anadromous, accomplishing the bulk of their growth in sea water. The overwhelming majority of salmonids cultured in sea water are members of the genera *Salmo* or *Oncorhynchus*.

These were both originally natives of the Northern Hemisphere; the former spawning in rivers entering the north Atlantic and the latter the northern Pacific Ocean. Salmon mariculture has spread far beyond the native range, with Chile now being one of the major producers of Pacific salmon species and Atlantic salmon being farmed on the Pacific coast of Canada as well as Chile and Australia.

Worldwide production of farmed Atlantic salmon (*Salmo salar*) rose from just over 110 000 t in 1988 to almost 650 000 t in 1997; nearly all seawater rearing takes place in cages in sheltered coastal waters, although there is a move toward using offshore sites. A small number of farms pump sea water into large silo-like tanks. These are used mainly for broodfish whose high value justifies the high capital and pumping costs. Norway remains the major producer, with almost half of the total production: Chile and Scotland both produce over 100 000 t annually. All producing countries export much of their farmed salmon, but for Chile and smaller producers such as the Faroe Islands salmon farming represents a major export opportunity and earner of foreign currency.

Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*Oncorhynchus kisutch*) are also farmed commercially in seawater cages. The annual production (1997) of chinook salmon was around 10 000 t (mainly from Canada and New Zealand) and that of coho was 90 000 t, almost 80 000 t of which were harvested in Chile. Around 250 000 t of rainbow trout (*Oncorhynchus mykiss*) are farmed annually; much of this is produced entirely in freshwater pond systems although in some countries, notably Chile, there is significant production based on the transfer of smolts to seawater cages.

The anadromous behavior and reliable homing of salmonids to the point of original release has meant that they can be ranched successfully. This is well demonstrated in Japan, where in the mid-1990s over 2 billion juvenile salmonids were released annually. By careful timing of release of high-quality smolts, return rates to harvest were raised to over 2%, with chum salmon (*Oncorhynchus keta*) making up 90% of the return. This is a profitable venture; largely because for this species smolts migrate to sea soon after initial feeding has begun, and are therefore cheap to produce in large quantities.

Milkfish (*Chanos chanos*) These diadromous fish have been cultured in South-East Asia for hundreds of years. The 1997 annual production of almost 400 000 t represents a small increase over the 350 000 t produced in 1988; reliance on harvests of juveniles from the wild and a lack of hatchery juveniles have probably restricted development of the industry. Major producing nations are Indonesia (168 000 t), Philippines (160 000 t) and Taiwan (60 000 t). Culture is in floating cages.

Flatfish The high retail price of many species of flatfish makes rearing an attractive proposition. Many years of research have been required to overcome the problems associated with the rearing of tiny larvae and their metamorphosis from roundfish to flatfish. Overall world production is low but increasing rapidly as future prospects are good. The majority of the 38 000 t of flatfish produced worldwide in 1997 (3000 t in 1988) was supplied by the bastard halibut (*Paralicthys olivaceus*), farmed in Japan. However, production of Atlantic halibut (*Hippoglossus hippoglossus*) in northern Europe, sole (*Solea vulgaris*) around the Mediterranean, and turbot (*Psetta maxima*) on the Atlantic coasts of France, Spain, and Portugal is increasing rapidly.

Sea bass and sea bream These names may be confusing as they are used to refer to a variety of species of fish. Here they are used for the European sea bass (*Dicentrarchus labrax*) and the gilthead sea bream (*Sparus aurata*). Production of both of these species in seawater cages in the Mediterranean began in the early 1980s, borrowing and adapting technology developed for the cage rearing of salmonids in northern Europe. In 1988 production of sea bass from around the whole Mediterranean was just over 1500 t; within 10 years this had risen to over 27 000 t. Over half of this came from Greece; Italy, Egypt and France are also significant producers, but most countries with a Mediterranean coastline are developing the culture of bass and sea bream. Gilthead sea bream production reached 45 000 t in 1997 (1800 t in 1988) with Greece again being the major producer, followed by Turkey and Spain. The rapid growth of the farming of sea bass and sea bream in the Mediterranean has been made possible by the reliable supply of high-quality juveniles from large hatcheries, each supplying many millions of juveniles each year. In these, often technically complex, hatcheries broodstock are spawned under controlled conditions. The delicate pelagic eggs are hatched and the larvae are supplied with live food, usually rotifers that have themselves been produced in the hatchery. The rotifers are fed on baker's yeast and several species of microalgae, also cultured in the hatchery. As the juvenile fish grow, they are fed on artemia or copepods and are eventually weaned onto dry diet: after this, weighing a few grams, they are ready to be transferred to sea cages.

Other species of sea bream, notably the Japanese sea bream *Pagrus major* are also cultured: annual production of this species is over 80 000 t.

Tuna Both the northern bluefin tuna (*Thunnus thynnus*) and the southern bluefin tuna (*Thunnus maccoyli*) are cultured (2000 t in 1997). Although current production is small, the successful use of high-seas cages has been demonstrated and high prices, consumer demand, and shortage of wild fish suggest that tuna culture will grow rapidly.

The Future

It is generally agreed that aquaculture, currently the fastest growing sector of the food industry worldwide will continue to grow in response to increasing demand for seafood, lack of growth in fisheries, and pressure on agricultural land. However, there are likely to be some changes from the present industry.

- *New species*. As the technology of hatcheries and holding facilities such as recirculation systems and open-ocean cages develops, a wider range of species will be cultured.
- *Bigger farms*. There has been a tendency in the salmonid farming industry to move from small units producing a hundred tonnes of fish annually to larger, thousand-tonne or more units. Ownership has passed from families to large, often multinational companies. Such farms are likely to be vertically integrated with hatcheries, freshwater units, and even feed and processing operations.
- *Better management of environmental impacts*. The mariculture industry has been criticized for adversely affecting the environment through pollution, transfer of diseases, effects of escaped fish, and destruction of mangroves and saltmarshes. This includes better planning of sites and reductions in wastes.
- Reduction in the dependence on fishmeal as a major constituent of the diet of farmed fish.
- *More combined culture*. At present most marine species are cultured in monoculture systems, in contrast to the polyculture of carp species in which different trophic levels are exploited by different species. An example of brackish-water polyculture is being developed in Indian, where fish and shrimp are grown together with salt-resistant rice. In the sea, pilot-scale projects combining cage culture of fish with that of filter feeding mollusks and seaweeds are being developed in Japan. The mollusks and seaweeds benefit from the nutrients produced as wastes by the fish in the cages above. Such a system therefore has the benefit of reducing wastes and producing salable produce as a low-cost by-product.
- *More interaction with fisheries*. This may be in the form of ranching or, as with lobsters and scallops – valuable but slow-growing species – the seeding of suitable growout areas. In some countries the major obstacle to the release of organisms into the wild is regulatory; legislation may need to be put in place to clarify ownership of released stock. The success of the Japanese mariculture industry demonstrates the benefits of collaborative management of the coastal zone by collectives.
- Improved hatchery techniques, bringing down the costs of juveniles and reducing the need for the production of live feed and collection of juveniles from the wild.

See also

Mariculture Diseases and Health. Mariculture of Aquarium Fishes. Mariculture of Mediterranean Species. Mariculture, Environmental, Economic and Social Impacts of. Ocean Ranching. Salmonid Farming.

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