AQUACULTURE

The Farming and Husbandry of Freshwater and Marine Organisms

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Preface

Much of the success of the green revolution lies in the planned systems approach that was followed in developing certain key crops. Yet husbandry of land animals in the developed world had already taken a similar approach, including the development of automation. Chicken, for example, are a highly efficient source of animal protein production. On a modern chicken farm, perhaps best called an industry, adequate fixed and variable inputs permit one man to produce 500 tons or more of meat per year. He obtains his chicks from a hatchery and only tends to feeding, watering, and cleaning devices. It is relevant here that part of the variable cost inputs, namely feed, is spent for fish meal, that is, cheap aquatic animal protein.

The question has been asked if one could rear aquatic animals in a manner similar to these chicken production-line assemblies. This question is pertinent, not only to obtain, for example, the fish meal protein base, but also because there are large areas available in the developing world where water is or can be supplied and where intensive *aquaculture** might well be practiced. Also, it has been said that it may be cheaper, pound per pound, to grow aquatic rather than land animals for food because they are of the same density as the medium in which they live and require only containers for their water rather than supporting and sheltering structures, such as stables and huts. Since man is a land dweller, it is logical that he applied scientific and engineering skills to land animal production first and foremost, especially since he could, and still can, gather, rather than grow and tend, fish from the sea and inland waters. That process—traditional fisheries—rather than aquaculture has

* Even though often called aquiculture—in consonance with agriculture—aquaculture is the etymologically correct term.

received significant technological inputs so that the weight of sea fish harvested per man per year in the well-mechanized fisheries for cheap sources of fish meal, the previously mentioned chicken feed, is easily twice or more that attained on a mechanized chicken farm.

Aside from the lack of attention to aquaculture so far, there exist in it biotechnical and economic obstacles of peculiar dimensions to efficiency upgrading: water rather than air is the environment of the animals we wish to rear; in part, this is the reason why animal husbandry in water is far less developed than the corresponding branch of agriculture on land. For instance, unused chicken feed and excreta—even at high densities—are easily disposed of, at least in the space where the animals grow. That poultry farms present off-site pollution problems is another matter, but at least the air in the chicken house is not full of feed or droppings. In contrast, in the water unused feed as well as metabolic products surround the animals, befoul the medium, and impose the need for continuous flushing, which requires either an overabundance of water or costly recycling schemes. Furthermore, young chickens—and calves and piglets after weaning—eat the same food as their parents; not so most cold-blooded aquatic animals. Their larvae undergo several transformations from hatching to their adult stages (e.g., six in the case of the shrimp) during which they neither resemble the parents nor consume the same food. In the life cycle, fish and invertebrates alike recapitulate their evolutionary history in the water, instead of warm-blooded animals *in ovo* or *in utero*. Growing fish and invertebrates requires, therefore, attention to larval survival and larval feeding and imposes constraints on successfully rearing them from the egg. At the same time, the large number of eggs they produce affords certain advantages, even for the selective rearing of desirable strains.

Man has tried for millennia to overcome these obstacles, and with some animals he has been very successful indeed; others hold considerable promise. In a few cases, helped by specially favorable conditions, man has been able to surpass the efficiency attained with chicken, producing more than 100,000 lb of flesh per man per year (e.g., mussels in the Bays of Galicia, Spain, and sewage-stream-fattened carp in Indonesia). In other cases, though not growing as much bulk, aquacultural entrepreneurs do a lucrative business (e.g., shrimp in Japan under rather unique socioeconomic conditions, trout in Denmark and the Snake River Valley of the United States, and milkfish and Chinese carp in Southeast Asia). Even for them, but especially considering the world's need for nutrition, it is clearly worthwhile to apply more technological and engineering principles to aquaculture than has been done in the past. The result would then be substantial improvements in production efficiency at various levels of intensity. One aim of this book is to provide a useful baseline for such endeavors by describing what is being done in aquaculture now in many parts of the world.

The division of the world into nutritionally and otherwise rich countries and poor and needy ones is a reality, much as one may deplore it, and aquaculture develops under somewhat different premises in each region. In the technically advanced countries it is strictly a question of producing mostly luxury food commodities at competitive costs for a diversified, often protein-glutted food market (or products for high monetary return or recreation). In the developing world the predominant problem is one of producing additional animal proteins, which may be so scarce there that any meat, unless excessively cheap, is a luxury commodity available only to the relatively wealthy few. The corollary here is that especially in developing nations herbivores or plankton filter feeders are most suitable for aquaculture, producing the most per surface or volume of water from the more-or-less natural amenities, such as solar energy, existing standing or flowing waters, and natural or man-enhanced fertility.

The rearing of herbivores as well as carnivores modifies the natural ecology of land or water by passing through the system energy and materials at a faster rate than that set there by natural evolution—faster than nature intended. This practice requires labor and installations and is likely to accelerate natural dysfunctions—waste accumulations and the like—which must be coped with through technical, hence economic, inputs. Thus an aquacultural product is likely to cost more per pound than many if not most that can be gathered through fisheries from natural aquatic populations. Aquaculture will not replace fisheries. However, it may, and in our opinion is likely to, supplement them increasingly as the natural production limit is reached in one after another of the large fishing areas of the world. True, there are presently unexploited fishing grounds in the Indian Ocean, the Indonesian Archipelago, Australian waters, and elsewhere that eventually could permit an expansion of traditional fishery products to perhaps double the present level. In addition there are such unused resources as the Antarctic krill where exploitation may become technically and economically feasible. But these areas have natural limits beyond which their yields cannot be sustained.

Seafaring, including the quest for fish, and the domestication of land plants and animals have enabled man to spread over the globe. We now wish to explore what species can be domesticated in the sea or in lakes and rivers, especially with the development of some technical mastery over the once alien, liquid portion of our biosphere. It is not surprising that aquaculture has advanced farther in fresh than in salt water and that mariculture is still in its infancy. Thus the only truly domesticated aquatic animals are carp and trout rather than saltwater creatures.

Whether we wish to grow crab or mullet, lobster or shrimp and whether the first consideration is to make money or to supply additional animal proteins in a country's diet, we should have complete manipulative mastery over the entire life cycle of the animal. Provided that ecological considerations and economic reasons prove (e.g., trout) or suggest (e.g., shrimp) that an animal can and should be reared the following should be considered. (1) *Control over reproductive biology* of the species in question is necessary. One should be able to produce offspring at will and at predetermined times. Lacking this level of control one should at least be able to gather the young in sufficient abundance (e.g., oysters) more than once a year, especially in the tropics. (2) Another set of problems common to all aquaculture concerns *nutrition* and *diseases*. As mentioned, different larval stages require different foods, and the exact nutritional requirements of but few species are known. The rearing of animals in close proximity in the water leads easily to their infection with viruses, bacteria, fungi, and multicellular parasites, many of which are only cursorily known. As in human populations, animals under crowding and stress, even if they are fish, are more likely to succumb to diseases than are calm, well-nourished ones, be it because of poor nutrition or for psychological reasons. Thus success in aquaculture requires an understanding of nutrition and diseases of a species and of their interplay with aspects of the animals' behavior. (3) Economically sound technology—*aquacultural engineering*—must be utilized. Technology here ranges from the extremely simple, such as the proper construction of ponds or of hand-operated sluice gates that mix fresh with salt water, to the more complex, such as sophisticated larval rearing schemes that employ pumps, filters, and ultraviolet sterilization of the water, all more or less automated. The book treats these three general areas of concern and involvement in sequence. Rearing practices of animals are arranged by species according to their occurrence in fresh, brackish, and salt water.

The book is an outgrowth of our longstanding interest in aquaculture, with individual practical experiences in cold, temperate, and tropical regions. A report prepared by two of us for the American Institute of Biological Sciences, under contract with the President's Council on Marine Resources and Engineering Development sparked the idea in 1968. Although that report may be considered as the nucleus of the present effort, a very considerable amount of new information has been added. Most of the new material and, in fact, virtually the entire book in its present guise is eminently the product of the writing talents and organizational abilities of the third author.

Our purpose in the book is to give an overview of present, and to some extent past, practices of food aquaculture the world over, within our language and subject to the following constraints. We do not wish to speculate excessively about what might be done if certain incipient technologies and scientific hunches were advanced and perfected. We can, of course, only report what is available in the literature and what workers in the field are willing to tell us. It must be understood that some aquaculture operations are highly competitive, purely profit-oriented ventures and that even scientists in them consider some facets of what they do their secrets, which are not to be published or otherwise divulged. Their practices are often experimental, however, and as likely to be scrapped as they are to be operationally perfected; these then would not represent "the state of the art" and would hardly contribute to the conservative report that it is our intent to give. In addition one must note that many practices, especially in the developing countries, are not reported in print. Thus we may well have missed some important items here and there. We can only add to our apology for this shortcoming that we were unable to prevent it. We have restricted ourselves to food species and to some mention of their foods, respectively. For reasons of space and unity we have omitted in our treatment ornamental or industrial living aquatic resources, such as pearls or aquarium fishes or marine colloids from red and brown algae.

News stories of the last decade show substantial preoccupation with the oceans and their use and abuse; the growing of crops in the sea is prominent in the former category. Much has been said in this context, often in glowing terms, that on closer examination has made little ecological or economic sense. We hope this book provides a basis on which such speculations can be measured. We have compiled a welter of information from literatures of various countries that should be useful throughout the world, especially in regions where it is difficult to come by much comparative material. But we realize that in a field as fast growing as this one we cannot be as up to date as we would like to be. We offer this caution to our prospective readers who, we hope, can acquire through our book a "wet green thumb."

The information given in this book comes from many sources, the most valuable and timely of which are interviews and correspondence with individuals working in the various areas of specialization. We acknowledge these contributions at the end of each chapter, but we also wish to express here our grateful appreciation for their generous assistance, as well as that of any others whose names we may have inadvertently omitted. The drawings were prepared by Ilyse Rosenthal and Ann Hinds, to whose skill and patience we are indebted, and we wish particularly to acknowledge the invaluable assistance of Anita Gunning with many of the tasks involved in the preparation of the manuscript.

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Contents

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General Principles and Economics

Husbandry of aquatic organisms, though a novelty to much of the world, has been practiced through the ages. Oyster culture, for instance, thrived in ancient Rome and Gaul. There are earlier, less certain reports of artificial propagation of fish; the legendary Chinese Croesus, Fan-Li, of the fifth century B.C., is said to have reared carps in ponds. Although the description of their arrangement is reminiscent of the legendary well-field system of ancient Chinese social organization, its authenticity is not established. It has been speculated that aquaculture may have even more remote roots in the highly organized ancient water-oriented civilizations of the Near East, in which fish were an important dietary component.

No matter the antiquity of aquaculture, the contribution of the world's waters to man's diet still stems largely from the hunting and gathering of fish and shellfish from untended stocks. There has been a spectacular increase in the production of world fisheries, but wild stocks of aquatic organisms are limited, and ecological reasoning suggests that we must eventually reach a ceiling on the harvest of wild aquatic organisms. Recognition of these facts, coupled with the increasing efficiency of communications and the establishment of international technical agencies, such as the Food and Agricultural Organization of the United Nations, has led to a nearly worldwide interest in the last two decades in the potential of aquatic husbandry.

Neither aquaculture nor any other method of food production will be a panacea for human nutritional problems, but all can and must contribute if the specter of hunger is to be banned. Aquaculture,* that is, the growing of aquatic organisms under controlled conditions, can make a unique contribution to nutrition in many parts of the world by virtue both of its extremely high productivity in many situations and the fact that aquatic crops are primarily protein crops rather than sources of starchy staple foods. In this regard, it should be noted that certain aquatic organisms may be better converters of primary foods than ruminants, fowl, or even pigs. Some, such as filter feeding fishes and mollusks, feed on microscopic plankton, which cannot be used directly by man.

Whereas many existing aquaculture enterprises, including some of the most successful, rely on supplying high-protein feed to produce a luxury product for human consumption, aquaculture has the potential of producing large quantities of lower-cost protein-rich food. This has been done in parts of the Orient, but elsewhere applied scientific, technological, and managerial skills must be improved and substantial seed funds must be provided if aquaculture is to assume comparable importance.

Aquaculture is by no means restricted to food production. Sport fishermen have for centuries relied on hatcheries to supplement wild stocks and will increasingly do so in the future as recreational needs among developed nations grow in the face of much environmental degradation. Bait organisms are cultured for both sport and commercial purposes. Propagation of ornamental fish and plants constitutes an important industry in some areas. Pearls are cultured in appropriate molluscan species, and goldfish (*Carassius auratus*) and other species are commercially reared for use as laboratory animals. We have, however, limited ourselves to those organisms which are raised for use as human food,† which must be judged as the most important function of aquaculture at this point in history.

Aquaculture also contributes to human nutrition through the production of unicellular algae for use in animal feeds. Human and other animal

* Even though the term aquiculture is often used—in consonance with agriculture—it must be stressed that aquaculture is etymologically correct.

† As the methods for growing certain fish (e.g., salmon, pay-as-you-go pond trout, and catfish) are the same whether they be used for market or for sport, the use of portions of the fish crop, the rearing of which we treat, may not be primarily but only secondarily for food.

waste is sometimes used in this process in a manner that is ecologically sound and, under certain conditions, perhaps less costly than traditional sewage disposal methods. Attempts have been and are being made to apply similar methods to the production of human food items. Obstacles to large-scale adoption of such methods are sociocultural as well as technical, in that people would have to learn to accept new and unusual foods. We believe that practical aquaculture for such purposes is relatively far in the future, whereas production of species presently used for food, in some cases involving the use of organic wastes, is imminent and in some cases has been accomplished. For this reason, for the sake of unity, and because the culture of fish, shellfish, and multicellular plants comprises a vast subject in itself, we shall treat only organisms raised to be consumed more or less directly by man.

We have attempted to bring together information on cultured organisms from all over the world. The necessity for such a treatment is pointed up, for example, by the present simultaneous experimentation with mullet culture in Israel, Taiwan, Hawaii, and Great Britain, the widespread adoption of hybrid tilapia, and the worldwide practice of oyster culture. It is hoped that this book will make some contribution to the coordination of such research and management practices and also help researchers to avoid costly and time-consuming duplication. In this regard, however, planned international and regional exchanges of information are at least equally important.

Following a discussion, in this chapter, of general principles of aquaculture, including biological and some economic considerations, the book is organized by groups of organisms: true freshwater fish, fish which can adapt to varying salinities, true marine fish, invertebrates (mostly marine), and plants. An appendix treats some principles of construction and management of ponds.

RANGES OF AQUACULTURAL PRACTICES

Aquaculture is akin to terrestrial agriculture in that it cannot economically be carried out just anywhere. A site for aquaculture must present certain natural amenities, particularly an ample supply of water of suitable temperature, salinity, and fertility. It is also necessary that the culturist exercise control through ownership, lease, or other means of secure holding; this consideration is problematical for marine and brackish water aquaculture in many parts of the world, including much of the United States, where the traditional view is that the sea, its shores, and its resources are common property, available to all. Where this attitude prevails, aquaculture is effectively thwarted. Elsewhere, aquaculture in coastal waters is fostered by protective grants or leases. In Japan, where some of the most advanced and the greatest variety of aquacultural enterprises are carried out and are strongly encouraged by all levels of government, the prefectural governments (comparable to states or provinces elsewhere) designate the areas to be used for aquaculture, and the local fishermen's cooperative associations, unique and highly effective organizations, allocate subareas to individual aquaculturists at no charge.

However the site is held, it must usually be modified to greater or lesser extent; the amount of time and effort expended on management varies considerably. In a general way, aquaculture practices may be characterized by the relative intensity of human effort applied to them. Such a treatment permits the following arrangement according to increasing inputs of capital and labor, often with corresponding increases in yields.

1. Transplantation of organisms from poor to better growing grounds, not considered aquaculture in this book, is sometimes classified as the least intensive form of aquaculture. It is most prevalent in the Soviet Union, where by 1965 more than 50 species of fish had been acclimatized in 1225 lakes, 80 rivers, and nearly 100 reservoirs.

2. Transplantation often involves hatchery-reared fish, and transplanted stocks may be partially or totally dependent on hatcheries for their maintenance. A well-known recent example is the successful introduction of the coho salmon (*Oncorhynchus kisutch*) to Lake Michigan. Hatchery propagation has also often been employed to augment stocks of naturally occurring species. This practice was particularly common in the United States and Canada during the late nineteenth and early twentieth centuries. At that time, large numbers of fish fry and very early larvae of invertebrates were released, almost invariably with no discernible benefit to the fishery in question. More recently, it has been shown in a number of instances that if young animals can be reared to a later stage before release they may ultimately contribute significantly to fisheries.

3. Fish and invertebrates may be induced to enter special enclosures where they are trapped and held until ready for harvest. This technique, with virtually no further labor input, is used successfully to grow shrimp and various euryhaline fishes in the Malay Peninsula and the Mediterranean area, respectively.

4. The foregoing technique may be intensified by fertilization and/or the installation of devices to control the rate of exchange of water. Such schemes are widely applied in the culture of milkfish (*Chanos chanos*) and shrimp in southeast Asia.

5. More complete control of stocking may be achieved through the use of artificial enclosures so constructed as not to permit entry of wild fish. Earthen ponds are the oldest and most common of such enclosures. In classical freshwater fish culture, as best exemplified by the polyculture of cyprinids in China, food for the fish is produced "naturally" by fertilizing the pond. It is to be noted that this level of aquaculture represents the dividing line between what might still be called subsistence aquaculture, albeit with a high application of labor, and endeavors demanding higher capital as well as intensive labor inputs. The maximum yields which can be achieved with labor-intensive subsistence aquaculture are around 5000 to 8000 kg/ha and occur in tropical and subtropical regions.

6. Pond culture may be further intensified by feeding the stock directly, a practice which is usually essential in enclosures constructed of cement or wood, in the increasingly popular floating net cages, or wherever carnivorous animals are raised. Examples of such high-intensity methods in practice include catfish farming in the southern United States, trout farming in the United States and Europe, and the culture of common carp (*Cyprinus carpio*), eels (*Anguilla japonica*), yellowtail (*Seriola quinqueradiata*), kuruma shrimp (*Penaeus japonicus*), and other animals in Japan.

7. Another culture method that merits special treatment is raft culture of sessile invertebrates and macroscopic algae. Although the source of stock may be natural production (hatcheries also play a role, notably in oyster culture in the United States) and food is not artificially provided, the construction and management of the growing facilities usually involve considerable labor and expense, so that raft culture must be considered an intensive form of aquaculture. Probably the highest yields ever attained through aquaculture have involved the use of rafts; for example, 300,000 kg/ha of mussels (*Mytilus edulis*) have been raised in the Galician bays of Spain.

Yields obtained by this method, or through culture in floating cages, depend, however, on a much larger area or volume of water than the one in which the installations are found; they depend also on adequate tidal or current exchanges whereby food is carried to and/or wastes are removed from the sessile (oysters or mussels) or enclosed (e.g., yellowtail) animals.

With the preceding categories in mind, the reader may judge the approximate intensity, in terms of labor and other costs, of any aquaculture enterprise. Unfortunately, however, there is much more information available on yields per unit of water surface or volume than on the

TABLE 1. SELECTED EXAMPLES OF AQUACULTURAL YIELDS ARRANGED BY ASCENDING INTENSITY OF CULTURE METHODS

CULTURE METHOD	SPECIES	YIELD [KG/(HA)(YEAR)] OR ECONOMIC GAIN
Transplantation	Plaice (Denmark, 1919–1957)	Cost: benefit of transplantation, 1:1.1–1.3 in best years (other social benefits)
	Pacific salmon (U.S.)	Cost: benefit, based on return of hatchery fish in commercial catch, 1:2.3–5.1
Release of reared young into natural environment	Pacific salmon (Japan)	Cost: benefit 1:14–20, on above basis
	Shrimp, abalone, puffer fish (Japan)	Not assessed; reputed to increase income of fishermen
	Brown trout (Denmark, 1961–1963)	Maximum net profit/100 planted fish: 163%
Retention in enclosures of young or juveniles from wild populations, no fertilization, no feeding	Mullet	150–300
	Eel, miscellaneous fish (Italy)	
	Shrimp (Singapore)	1,250
Stocking and rearing in fertilized enclosures, no feeding	Milkfish (Taiwan)	1,000
	Carp and related spp. (Israel, S.E. Asia)	125–700
	Tilapia (Africa)	400–1,200
	Carp (Java, sewage streams) (¼–½ of water area used)	62,500–125,000
Stocking and rearing with fertilization and feeding	Channel catfish (U.S.)	3,000
	Carp, mullet (Israel)	2,100
	Tilapia (Cambodia)	8,000–12,000
	Carp and related spp. (in polyculture) (China, Hong Kong, Malaysia)	3,000–5,000
	Clarias (Thailand)	97,000