1
Introduction

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1.1 WHAT IS AQUACULTURE?

Give a person a fish and you feed them for a day; teach them how to grow fish and you feed them and their descendants for their lifetimes.

(somewhat modified from a Chinese proverb)

Aquaculture continues to develop rapidly, especially through its growth in Asia. World aquaculture production is increasing much more rapidly than animal husbandry and capture fisheries, the other two sources of animal protein for the world's population. There is widespread recognition that seafood production from capture fisheries is at or near its peak, and that aquaculture will become increasingly important as a source of seafood production, and ultimately the main source. There is widespread public interest in aquaculture. This is the context in which this textbook is written and we trust that it will convey some of the excitement of the rapidly developing discipline of aquaculture.

The term 'seafood' is used inclusively in this textbook, i.e. for all animal and plant products from aquatic environments, including freshwater, brackish and marine environments[1]. The term 'shellfish', according to common usage, describes aquatic invertebrates with a 'shell'. In this way, bivalve and gastropod molluscs, decapod crustaceans and sea urchins are combined, while recognising the extreme diversity of morphology and biology within this grouping. The two groups that overwhelmingly constitute shellfish are the bivalves (oysters, mussels, clams, etc.) and decapod crustaceans (shrimp, crayfish, crabs, etc.). The other major group of aquatic animal that is cultured is fish, also known as finfish. 'Fish farming' is used in the sense of aquaculture of fish, crustaceans, molluscs, etc., but not plants.

There are many different forms of aquaculture and, at the outset of this book, it is important to establish what aquaculture is, what it isn't and what distinguishes it from capture fisheries.

> The definition of aquaculture is understood to mean the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants. Farming implies some form of *intervention* in the rearing process to enhance production, such as regular stocking, feeding and protection from predators. Farming also implies individual or corporate *ownership* of stock being cultivated.
>
> *(FAO, 2006)*

> For statistical purposes, aquatic organisms that are harvested by an individual or corporate body that has owned them throughout their rearing period contribute to *aquaculture* while aquatic organisms that are exploitable by the public as a common property resource, with or without appropriate licences, are the harvest of *fisheries*.
>
> *(FAO, 2006)*

The two essential factors that together distinguish aquaculture from capture fisheries are:

- *intervention* to enhance the stock;
- *ownership* of the stock.

[1] With the exception of the final chapter, Chapter 26 The Next 20 Years, which focuses on edible products ('Food fish') and food security. The terms used in Chapter 26 are defined in its Introduction.

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Thus, a structure to which fish are attracted and caught (e.g. a fish-aggregating device (FAD) floating in the open ocean) may be owned, but this does not confer ownership of the stock of attracted fish. Furthermore, the FAD facilitates capture, but does not enhance the fish stock that is being captured. This is capture fisheries production. Hatchery production of juvenile salmon is aquaculture: they are owned by the hatchery and may be sold as fingerling fish. Their ultimate capture, after being released into rivers to which they eventually return to breed, is a fishery. The released fingerlings enhance the stock, but they become a common property resource. The same situation applies where hatchery-reared fish fingerlings are sold to fishing clubs and local government bodies to be stocked into lakes and dams to improve recreational fishing.

Hydroponics, the cultivation of terrestrial plants with their roots in dilute nutrient solutions instead of soil, isn't aquaculture. Hydroponics is an alternative method for growing terrestrial plants.

Activities constituting aquaculture production, according to FAO (2006), are:

- hatchery rearing of fry, spat, postlarvae, etc.;
- stocking of ponds, cages, tanks, raceways and temporary barrages (e.g. dams) with wild-caught or hatchery-produced juveniles to be reared to market size;
- culture in private tidal ponds (e.g. Indonesian 'tambaks');
- rearing molluscs to market size from hatchery-produced spat, transferred natural spatfall or transferred part-grown animals;
- stocked fish culture in paddy fields;
- harvesting planted or suspended seaweed;
- valliculture (culture in coastal lagoons).

1.2 ORIGINS OF AQUACULTURE AND AGRICULTURE

There were a number of independent origins of small-scale agriculture and a substantial variety of crops were domesticated for farming. Small-scale agriculture appears to have first developed about 10 000 years BC in the Fertile Crescent of south-west Asia, corresponding roughly to the modern-day region of Syria, Israel and Iraq, as human populations changed from hunting–gathering to cultivating crops that included wheat, barley, lentils, chickpeas, etc. (Fig. 1.1). Farming of cereals and other crops spread to adjacent regions. Subsequently, the farming of cereal crops arose independently on other major landmasses. Rice cultivation began in Asia about 7000 years ago. Sorghum and millet cultivation, and maize cultivation, developed somewhat later in Africa and America, respectively. These changes from hunting–gathering to farming cereal crops caused profound changes in lifestyle, from a nomadic to a settled existence. They resulted in greatly increased productivity from the land for human consumption and increased human populations per unit land area as a consequence. Whether quality of life improved in the early farming communities is debatable: diet became less varied and conditions became more favourable for disease.

The origins of aquaculture are much later. Culture of common carp (*Cyprinus carpio*) was developed thousands of years later in China, where the carp is a native species (Fig. 1.2). The first aquaculture text is attributed to a Chinese politician, Fan Lei, and is dated about 500 BC (Ling, 1977). Fan Lei attributed the source of his wealth to his fish ponds: so his fish culture was more than a hobby. However, in Africa, America and Australia, aquaculture was not practised until it was introduced in recent centuries.

The late origin of aquaculture compared with agriculture and its failure to develop in some continents is partly because humans are terrestrial inhabitants. We cannot readily appreciate the parameters of aquatic environments and there are environmental factors that may profoundly affect aquatic organisms, such as:

- very low solubility of O_2 in water;
- high solubility of CO_2 in water;
- pH;
- salinity;
- buffering capacity;
- dissolved nutrients;
- toxic nitrogenous waste molecules;
- turbidity;
- heavy metals and other toxic molecules in solution;
- phyto- and zooplankton concentrations;
- current velocity.

These can only be rigorously measured with modern instrumentation.

Many of the diseases that afflict aquatic organisms are quite unfamiliar to us. Furthermore, virtually all the animals used in aquaculture are poikilotherms (their body temperature is variable and strongly influenced by environmental temperature) ('cold blooded'). Their metabolic rates, and all functions depending on metabolic rate, are profoundly influenced by environmental temperature in ways that we do not experience as 'warm-blooded' mammals.

The difficulties of appreciating the influences of these environmental factors still apply today, causing aquacul-

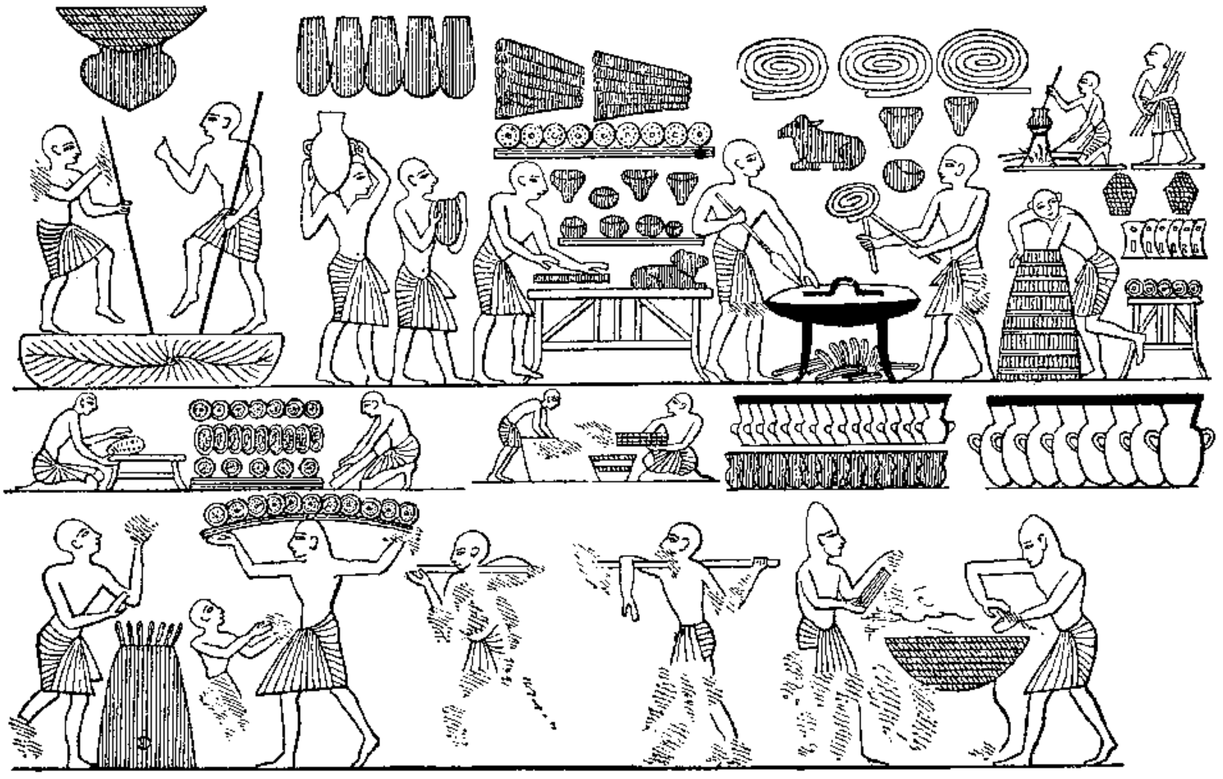

Fig. 1.1 The court bakery of Ramses III. From the tomb of Ramses III in the Valley of the Kings, twentieth dynasty. (*The Oxford encyclopedia of ancient Egypt*, copyright expired.)

Fig. 1.2 The common carp (*Cyprinus carpio*). (Photograph by Piet Spaans.)

ture programmes to have a relatively longer development period than other forms of food production. 'Even when tested technologies are adopted, the construction of physical facilities (particularly pond farms), solution of site-specific problems, the building up of the productivity of the system and, above all, attainment of skills by workers take considerable time' (Pillay, 1990). In agriculture we are much more readily able to appreciate the parameters influencing the success or otherwise of the output, and we have a very long history of attaining the skills needed.

A further major consequence of the late origin of aquaculture is that there has been relatively little genetic selection for many species and this is compared with the highly selected plants and animals of agriculture. Modern agriculture is based on organisms that are vastly different from their wild ancestors, and in many cases their wild ancestors no longer exist. This selection for desirable traits took place steadily and without any scientific basis over thousands of years of domestication. It was more intense last century with scientific breeding programmes. Modern agriculture would be totally uneconomic and the current world population would starve without these domesticated and genetically selected agricultural plants and animals. Much of aquaculture, by contrast, is based on plants and animals that are still 'wild'. There are, however, species that have been subject to strong selection, hybridisation, and molecular and genomic techniques (Chapter 7), such as:

- common carp;
- Atlantic salmon;
- rainbow trout;
- tilapia species;
- channel catfish.

Their breeding is based on broodstock that differ substantially from their ancestors in their genetics. Many other aquaculture species are based on wild broodstock obtained from natural populations. In some cases the life cycle has not yet been 'closed', i.e. the species has not been reared to sexual maturity and then spawned on a regular basis under culture conditions. Until the life cycle is closed, there is minimal potential for selective breeding.

1.3 AQUACULTURE AND CAPTURE FISHERIES PRODUCTION

Fishing activities, whether they are spearing individual fish, collecting shellfish from a rocky shore or coral reef, using a cast net, or capturing schools of fish with huge nets from factory trawlers that ply the world's oceans, are all hunting–gathering regardless of the degree of technology. As capture fisheries production currently exceeds aquaculture production, hunting–gathering activities remain the principal source of seafood. These fisheries suffer problems that are fundamental to hunting–gathering:

- variable recruitment and consequent unpredictability of stock size;
- difficulties in assessing stock size and its capacity for exploitation;
- difficulty in regulating exploitation to match the stock size;
- relatively low productivity.

The natural productivity of the world's water masses, fresh, brackish and marine, is huge, but finite; and a finite amount of plant and animal products can be harvested by fishing. For instance, the mean harvest from oceans that can be obtained for human consumption or processed for use in fish meal is ca. 2.5 kg per hectare of ocean surface per year. Furthermore, this huge but finite amount of harvest is within our current fishing capacity. Many of the world's major capture fisheries range from being heavily exploited to heavily overexploited, and production from capture fisheries has reached a plateau of ca.90 million t/year[2], around which it now fluctuates annually (Fig. 1.3). Global capture fisheries production increased to 93 million tonnes in 1994 and since then has fluctuated between 89 and 97 million t/year, with an overall mean increase of <1% per year.

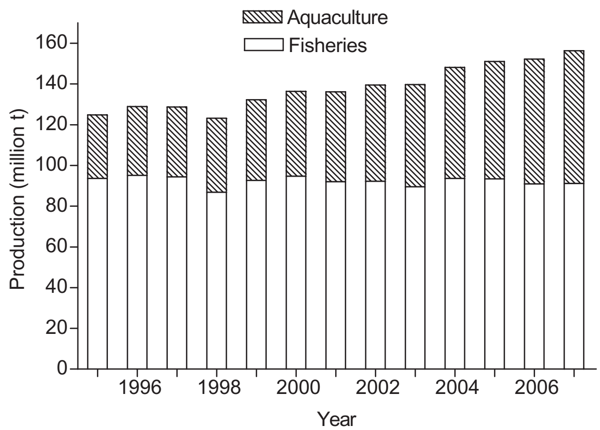

Fig. 1.3 Global production of capture fisheries and aquaculture per year from 1995 to 2007.

There are two further factors in capture fisheries production. About one-third of capture fisheries production is used to make fish meal, i.e. dried fish products, based on sardines, anchovy, fish wastes, etc. Fish meal is used as a source of animal protein and lipids in feeds in agricultural animal husbandry, e.g. pig feeds, but it is also extensively used in feeds for aquaculture (section 9.10). Thus, the effective annual production from global capture fisheries for direct human consumption is in the order of 60 million t/year. The other 30 million tonnes subsequently finds its way into the human diet by indirect processes.

A further factor that does not appear in FAO fisheries statistics is the substantial proportion of capture fisheries that is bycatch (non-target catch) and discards (e.g. under commercial size). A high proportion of these die. Alverson *et al.* (1994) estimated a mean of 27 million t/year of bycatch and discards from global commercial fisheries. They considered this conservative as it didn't include data on some invertebrate fisheries, and recreational and subsistence fisheries. Bycatch and discards vary according to

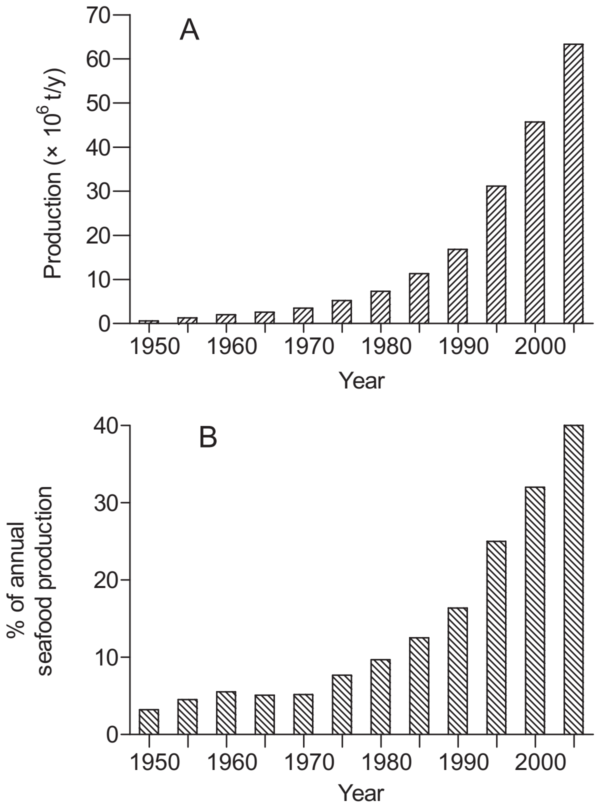

Fig. 1.4 A. Global production of aquaculture per year from 1950 to 2007. **B.** Aquaculture production as a percentage of global seafood production per year.

the nature of fishery and other factors. Alverson *et al.* (1994) rated marine shrimp trawl fisheries wherever they occur as consistently being among the highest bycatch fisheries. In view of the increase in world fishery effort since 1994, it is reasonable to assume that this wastage amounts to about 30 million t/year, i.e. a third again on top of the 90 million t/year global fishery.

In contrast to capture fisheries, aquaculture production of animals and plants grew at a mean rate of 8.1% over the same period (Fig. 1.4A). The increase in global aquatic animal and plant supply in recent decades has come largely from aquaculture. In 2007, aquaculture contributed 42% of total global seafood production (Fig. 1.4B) and it will continue to increase in relative importance. It is clear that further increases in supply from aquatic environments will come largely from aquaculture. Unlike capture fisheries, aquaculture is not limited by the natural productivity of the world's water masses. It is therefore not surprising that aquaculture production has been increasing and will inevitably overtake global capture fisheries production. In view of the fact that the percent contribution of aquaculture to global seafood supply seems to be increasing exponentially (Fig. 1.4B), this may happen sooner rather than later.

Aquatic plants (very predominantly seaweeds) contribute substantially to aquaculture and capture fisheries production, especially to the former (section 13.2.1). Aquatic plant productions from aquaculture and capture fisheries were ca. 14.9 million and 1.1 million tonnes, respectively, in 2007 (FAO Fishstat Plus, 2009)[2]. The relative proportions by weight and value of fish, molluscs, crustaceans and plants from aquaculture in 2007 are shown in Fig. 1.5. Fish constitute about half the weight and value of aquaculture production. Plants and shellfish each constitute about 20% of the weight. There are, however, major changes between relative weights and relative values of plants and shellfish. Molluscs decline in relative value. Plants decline even more in relative value and together molluscs and plants constitute a bit less than a quarter of the value of aquaculture production. Crustaceans (mainly marine shrimp) show a very large increase in value to almost a quarter of the value. Fish remain at about half the value of aquaculture production. This has significant implications for countries such as China.

Food security for the world's population, especially in poorer countries, is a major factor constraining international organisations such as the FAO (Chapter 26). To put aquaculture and fisheries production into the perspective of providing animal protein for the world's current population: global production of slaughtered meat from livestock (pork, beef, chicken and lamb) is in the order of 250 million t/year compared with about 60 million t/year from capture fisheries (for direct human consumption) and 52 million tonnes from aquaculture (excluding aquatic plants). This 110 million tonnes from aquaculture and fisheries is pre-slaughtered weight, and slaughtered weight (after removal of viscera, heads and shells) is probably around 50–60%. This value is not easy to estimate as it varies markedly with the kind of animal and country of consumption. Consequently, seafood makes up about 20% of all animal protein production per year. Aquaculture is a modest 7% of all animal protein production/year based on these calculations. With fisheries production/year almost

[2]Unless otherwise stated, all production and value data given for aquaculture and capture fisheries in this textbook are derived from the FAO online site Fishstat Plus 2009. The software may be downloaded and installed from http://www.fao.org/fishery/statistics/software/en.

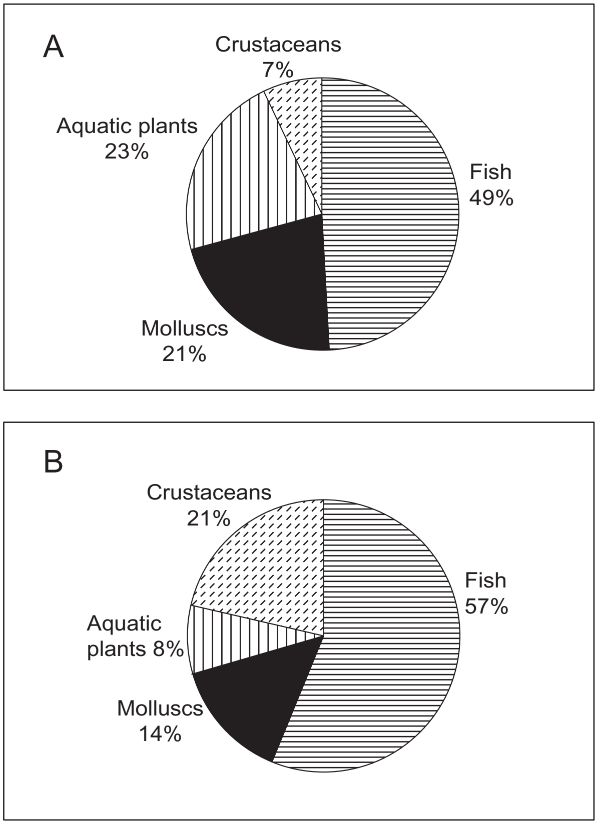

Fig. 1.5 Relative proportions of fish, molluscs, crustaceans and aquatic plants in global aquaculture production in 2007. **A**. By weight. **B**. By value.

static and unlikely to increase much, and, while livestock production is increasing at about 2% per year, aquaculture is increasing at 8% per year. This roughly estimated value (7%) of aquaculture's contribution to world animal protein production is an increase from 3.5% in 1993, estimated by New (1997).

1.4 THE 'BLUE REVOLUTION'

The rapid increase in aquaculture production in the 1990s led to suggestions that aquaculture was undergoing a 'Blue Revolution' that would transform the productivity of marine and other aquatic environments with new technology (e.g. Holmes, 1996; Entis, 1997) (Fig. 1.6). This envisaged a revolution in productivity similar to the 'Green Revolution' in agriculture during the decades following World War II. The Green Revolution occurred 'where concentrated research developed the basis for the agricultural practices in use today (e.g. mechanisation, heavy fertilisation, heavy pesticide use, irrigation, genetically improved stocks, advanced feed formulations)' (Hopkins, 1996).

The great, almost exponential, increase in the quantity of animal and plant aquaculture production in the two decades from 1987 to 2007 came mainly from increases in freshwater and marine aquaculture. There was a greater absolute increase in the marine environment in total aquaculture production, which includes considerable aquatic plant production (Fig. 1.7A). In terms of specifically animal production, however, and hence protein production directly for human consumption, the increase was substantially greater from freshwater aquaculture (Fig. 1.7B). The annual rate of production of aquatic animals in freshwater environments increased by 25 million tonnes over these two decades compared with an increase of 15 million tonnes in the rate of annual production in the marine environment. This clearly establishes freshwater as the major environment of aquatic animal production (Fig. 1.7). The large increase in seaweed production in the marine environment is important as a source of income, but it is of low value as an immediate source of protein for human consumption.

There is a further very important statistic about the growth in aquaculture production over recent decades: it was particularly driven by growth of the industry in China (Table 1.1). Furthermore, dividing between developing countries (FAO classification), which include China, and developed countries, 50 out of the 51 million t/year increased rate of global aquaculture production over the period 1987 to 2007 came from developing countries (Table 1.1). Aquaculture production in these countries increased at the remarkable rate of 9.0% per year over these two decades (Table 1.1). Compared with this, the 1.9% per year growth of aquaculture production in the developed countries was modest. The 'Blue Revolution' in aquaculture, like the 'Green Revolution' in agriculture, occurred primarily in developing countries. China alone showed an increase of about 35 million t/year over the period 1987 to 2007 at the even more remarkable rate of 10.1% per year (Table 1.1). It was the driving force of aquaculture expansion in the developing countries and the world. By 2007, China accounted for almost two-thirds of global aquaculture production (Table 1.1). In view of the fact that the growth in aquaculture production of aquatic animals in particular occurred predominately in freshwater systems, which are often anything but blue, it might be appropriate to call the huge increase in aquaculture the 'Brown Revolution'.

Fig. 1.6 Sea Station 3000 is a fully submersible 3000 m^3 seacage (24 m diam × 16.5 m tall). In operation the seacage is submerged to below 10 m depth, ca. 800 m off the Kona Coast of the Big Island of Hawaii. It is stocked with up to 70 000 *Seriola rivoliana* (see cover photograph). The Offshore Site Manager is standing on the spar of the semi-submerged structure. (Photograph from Kona Blue Water Farms, Inc. Kona Kampachi®.)

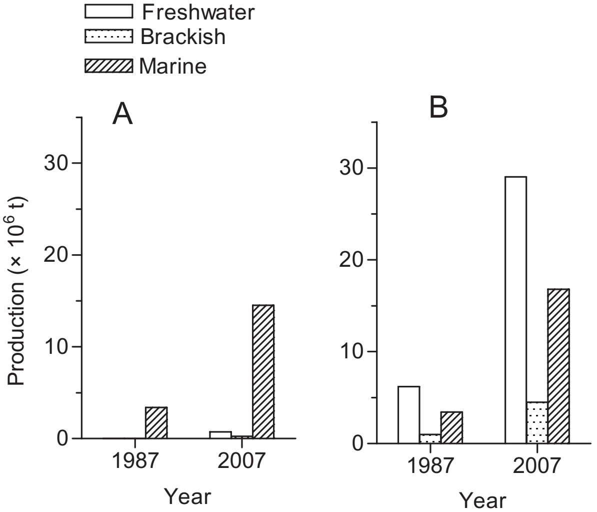

Fig. 1.7 Increases in global aquaculture production between 1987 and 2007 by environment.
A. Increase in plant production. **B**. Increase in animal production.

It would be misleading, however, to see aquaculture developing purely as an expansion of pond culture. For example, there are a number of sophisticated developments in disease control (section 19.5.4), genetics (section 7.8) and feed formulation (section 8.8).

The 10 major countries in terms of quantity of aquaculture production in 2007 are shown in Table 1.2. All except Chile are Asian countries and, according to FAO classification, all except Japan are developing countries. The huge gap between China and the following countries is notable.

Although the developing Asian countries have aquaculture industries of high-value products, such as shrimp and scallops, for lucrative export markets, a high proportion of aquaculture in these countries continues to be from traditional pond culture of freshwater fish, especially carps and other cyprinids (Chapter 14). Fig. 1.8 shows that carps together with other cyprinids are by far the most important fish by weight in global production. Cyprinid production is a magnitude greater than the next two major groups of fish in aquaculture, tilapia and salmonids: ca. 20 million t/year versus ca. 2 million t/year for each of the latter two. Cyprinids are the most valuable fish in total global production, but have substantially lower value per unit weight

Table 1.1 Global aquaculture production in 1987 and 2007 by developing and developed countries. Data for China are also shown.

		Global aquaculture production		
	Population (1999) (millions)	1987 (000 t)	2007 (000 t)	Mean % increase/year
World	5978	13 962	65 190	8.0%
Developing countries	3664	10 855	60 676	9.0%
% of world total		77.7%	93.1%	
Developed countries	2314	3 106	4 515	1.9%
% of world total		22.2%	6.9%	
China	*1243*	*6 011*	*41 173*	*10.1%*
% of world total		*43.1%*	*63.2%*	

Table 1.2 The top 10 countries in terms of weight of total aquaculture production in 2007.

Sequence	Country	% of world production	Asian country	Develping country
1	China	63.2	Y	Y
2	India	6.1	Y	Y
3	Indonesia	4.8	Y	Y
4	Philippines	3.4	Y	Y
5	Vietnam	3.4	Y	Y
6	Korean Republic	2.1	Y	Y
7	Thailand	2.1	Y	Y
8	Japan	2.0	Y	
9	Bangladesh	1.5	Y	Y
10	Chile	1.3		Y

than salmonids and are only twice as valuable as the latter: ca. US$19 billion/year versus ca. US$10 billion/year for salmonids.

These freshwater fishes are part of the reason for China's percentage of global aquaculture output being ca. 50% by value compared with 70% by weight in 2007. Further factors are that China provides more than 70% of the world's seaweed production and two-thirds of the molluscs (mainly bivalves). Both are of relatively low value (Fig. 1.5).

Freshwater fish are often cultured together as complementary species (polyculture; section 2.3.5). These fish species are herbivores, omnivores and detritivores, feeding low in the food chain and requiring little supplementary input of feeds. This aquaculture often involves simple ponds, basic technology and low stocking densities. The production is often enhanced by using inexpensive organic fertilisers such as farm animal faeces and crop residues to feed the cultured fish, and to promote primary production in the ponds (integrated culture; section 2.3.6). In rural communities where animal protein is scarce and is prohibitively expensive from other sources, cultured fish form the major, if not the exclusive, source of animal protein.

A number of factors are responsible for the outstanding increase in aquaculture production in China (Cen and Zhang, 1998). However, the major factor has been a great increase in the surface area of ponds, other freshwater environments and shallow coastal environments committed to aquaculture. Listed below is a series of important factors.

- The Chinese government deliberately embarked on a large-scale programme to develop aquaculture.

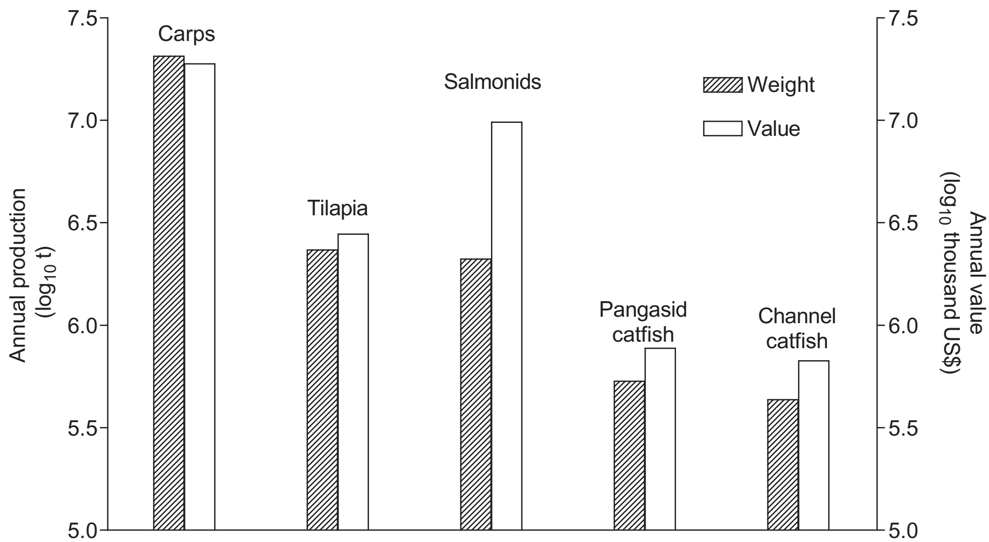

Fig. 1.8 Annual production of major groups of fish. Note that both *Y*-axes are logarithmic and there are magnitudes of differences.

- China has identified huge areas of potential sites for aquaculture and is prepared to use them to a large extent, i.e. 2.6 million ha of suitable coastal sites and 17.5 million ha of inland freshwater sites.
- Mariculture utilisation of shallow sea and mudflat areas was 25.1% in 1995 compared with 3.9% in 1978, and offshore areas used for mariculture have been extended offshore from 10 m to 50 m depth.
- Utilisation for aquaculture of inland waters was 25.5% in 1995 compared with 4.3% in 1978 (this 4.3% already consisted of 100 500 ha).
- Productivity per unit area, although still generally low, has been increased through research, extension and better technology.
- The number of species in culture has greatly increased, including high-value species for international markets such as marine shrimp, crabs, scallops, abalone, eels and rainbow trout.
- Sixty exotic species were introduced from abroad, 20 new species have been domesticated from wild populations and about 30 species have been improved through hybridisation and stock selection programmes.
- Huge numbers of fingerlings and juveniles are produced from many large hatcheries.

Unlike the Green Revolution, where technological developments played a major role in increased productivity, the outstanding growth of aquaculture in China has not depended on major technological developments. The growth has resulted in particular from upscaling by increasing the areas devoted to ongrowing aquaculture, increasing hatchery output and increasing the number of species cultured.

The result of this deliberate programme to promote aquaculture is that China leads the world in being one of the few, or perhaps the only country, in which aquaculture production substantially exceeds fisheries production. China has already achieved the anticipated stage when the balance of production between aquaculture and fisheries shifts to the former. Aquaculture production is more than double fisheries production.

It may not seem surprising that China, as the country with the largest population, is the greatest aquaculture producer. Some production versus population size data are presented in Table 1.1. China's aquaculture production is ca. 36 kg/person/year. Mean production for all developing countries is ca. 17 kg/person/year and for developed countries it is <2 kg/person/year. Taken at face value these figures are misleading. For instance, China produces a lot of seaweed (see above), which is not much used for human consumption, and, like other Asian countries, it exports high-value aquaculture products to developed countries.

In considering production versus consumption, there is a further complication when the data for total production

Table 1.3 Annual production of food fish[1] (t, million) from aquaculture and capture fisheries in the major regions of the world. Food fish consumption/person/year is also included.

	Africa	North America	Central America	Asia	Europe	Oceania	World
Total food fish production	8.0	6.8	10.9	82.3	15.9	1.6	134.6
Non-food use	–1.2	–0.9	–12.6	–10.1	–3.5	–0.4	–28.8
Imports	2.5	5.0	1.3	12.5	15.4	0.5	37.3
Exports	–1.8	–3.1	–3.8	–14.6	–12.8	–0.9	–38.8
Total food supply[2]	7.6	8.0	4.0	70.2	15.2	0.8	106.7
Consumption (kg/person/year)	8.3	24.1	8.7	17.8	20.7	24.6	16.4

[1]Food fish in this table refers to fish, crustaceans and molluscs destined for human consumption (see Chapter 26).

[2]Total food supply is the summation of the positive (production and imports) and negative (non-food use and exports) values. (FAO Fisheries and Aquaculture statistics.)

of edible sea food ('food fish') from aquaculture together with capture fisheries are considered (Table 1.3). As the Asian region includes the major aquaculture producers, it has by far the greatest production, but the European and North American regions have relatively greater imports. Despite the very high production of seafood in Asia, when the total available supplies of edible seafood are related to population sizes, the consumption in kg/person/year is greatest in Europe and North America (Table 1.3). These affluent regions also consume the greatest amounts of animal products from animal husbandry. Affluence supports high consumption of animal protein from both land and sea. The African countries, which on average have a low intake of animal products/person/year from animal husbandry, also have a low consumption of seafood.

These differences are further discussed in Chapter 26.

There is another contrast between aquaculture in the developing Asian countries and in developed countries. Over 60% of fish production in developed countries is based on high market-value species of carnivorous fish (Fig. 2.8). These fish are reared in monoculture at high stocking densities and need inputs of high-protein feeds. High-protein feeds are expensive and usually require fish meal as sources of animal protein and lipids for the carnivorous diet. Thus, this form of aquaculture uses low market-value products from fisheries as feed to increase their value in the final products of culture. This is inefficient (section 2.3.1).

A variety of factors have affected particular aquaculture industries, e.g. section 16.9, but environmental issues are a major factor consistently limiting the growth of aquaculture industries in developed countries (Chapter 4).

All agriculture and aquaculture needs environmental modifications on various scales to enhance production. For instance, grain farming such as wheat farming has irreversibly destroyed the environment in countless millions of hectares around the globe, with:

- native vegetation clear-felled;
- soil structure destroyed;
- soil eroded;
- extinctions or near extinctions of native species dependent on the original environment;
- introductions of exotic and pest species.

On the basis of contemporary environmental awareness it is very unlikely that grain farming would be permitted or even considered on this scale. However, the environmental damage has occurred over hundreds and thousands of years, is irreversible, and the alternative to grain farming is that the world population starves.

There have been fisheries for tens of thousands of years. However, since global fisheries have reached the point that it is no longer possible to extract more products (Fig. 1.3), it is inconceivable that they are not having widespread impacts on all aquatic ecosystems. These profound impacts are difficult to determine, but the *Sea Around Us* project is attempting this. 'Broadly, the work of the project is aimed at a reappraisal of fisheries, from the benign activity that many interested people still perceive them to be, to a realization that *they have become the driver for massive loss of biodiversity in the ocean* (italics added) (Pauly, 2007). There have been studies (e.g. Myers and Worm, 2003) showing the flow-down effects to lower trophic levels of overfishing predatory fish, so that the community structure is changed. Environmentally sound aquaculture may be a better alternative to fisheries for more than just increased seafood production.

Agriculture and fisheries are part of our heritage, but aquaculture, especially in the developed countries, is a latecomer and has to make its way in regulatory circumstances that are much more rigorous. Agriculture and fisheries are accepted despite their massive environmental damage because we depend on them as necessary sources of food. Aquaculture must develop within the constraints of comprehensive, sometimes unreasonable, environmental regulations in developed countries. It also has to develop within the constraints of existing stakeholders who may lodge objections to the proposed aquaculture development, e.g. for interfering with recreational boating, for noise that is unacceptable to nearby coastal communities. If the aquaculture farm is a long-standing fixture before the marina is proposed or the coastal community begins to develop in the region, these objections are more difficult to sustain, but this usually isn't the case. Many proposed projects founder on the number of permits and approvals required, legal and administrative costs, and the duration of processes in obtaining the final approval to go ahead with the project. There is widespread recognition in developed countries that aquaculture is the future if we are to meet the growing demand for seafood. It seems, however, that the governments of some developed countries are prepared to import increasing amounts of cultured seafood rather than facilitate growth of the industries within their countries. The greatest rate of increase in aquaculture production in developed countries, 6.5% per year, occurred some time ago in the decade 1966–1976. It was down to increasing by 1.9% per year over the period 1997–2007 (Table 1.1). This seems very low compared with the developing countries, although it is not much less than the 2% increase per year in livestock production. The rate of aquaculture growth in developed countries over the next decade will be interesting. It will strongly depend on government policies, for example:

- to what extent they are content to accept increasing seafood imports;
- to what extent they seek to enhance within-country production.

If it is the latter, they will need to do more to 'take the brakes off' and promote new aquaculture ventures. Major growth of aquaculture will not occur in the face of government indifference and over-regulation. In developing countries, the aquaculture industry growth has involved governments making decisions to facilitate aquaculture and particular aquaculture industries (section 1.8.1).

1.5 AN ALLEGORY

Short-tail lums are moderate-sized herbivores that weigh up to 50 kg. Some of their meat is sold on the local market, but most is packaged, frozen and exported to Asian markets where it is highly valued. Harvesting is based on shooting lums at night when they are active. The lums are fixed in a spotlight and shot by professional hunters riding on the backs of four-wheel-drive vehicles. However, as the populations were harvested at unsustainable levels it was necessary to drive further and longer to find lums. Furthermore, the remaining short-tail lums were vehicle shy and the vehicles had to drive faster and travel further into the bush, smashing down swathes of bushes and small trees. Some similar-sized carnivorous mammals were also shot because of limited time for careful identification. In fact, as the lums became increasingly rare, the strategy became to shoot first and check later when moving mammals were sighted. Increasing numbers of the non-target mammals were shot in this way, but they were of little commercial value. The short-tail lum industry became marginally profitable and numbers of hunters left for other employment.

Amateur lum hunters were affected by the diminishing populations and sent a delegation to raise the issue with the appropriate government Minister. It was proposed that reserves for short-tail lum protection be established. Some biologists, however, pointed out that the rates of recovery of short-tail lum populations, and the other diminished mammal populations, would not be limited by their rates of reproduction. Population recoveries would be limited by the long period required for recovery of their environment.

Independently, a farm to raise short-tail lums was proposed in the region. Careful planning was made for the lum farm to minimise environmental impacts and to meet all the requirements for a new animal production venture. The lums would be farmed at relatively high density and fed a comprehensive diet of grain, pelleted feeds and chaff, instead of grazing over a large area. The economic viability of the proposal was demonstrated. The short-tail lum breeding stock would be obtained from other farms with semi-domesticated stock. The proposal went to the Department of Primary Industries, Enterprise and Environment after two years of planning and discussion with local, state and national government bodies to meet the criteria for the new development. The Department published the proposal and invited submissions from the various stakeholders.

When asked, most people recognised that farming lums was the only solution to maintain or obtain more lum products. However, they did not want a nearby farm (NIMBY – Not In My Backyard). Protest meetings were organised, including the remaining professional hunters and a visiting habitat activist. Deputations were made to the Department and local politicians.

The bases for oppositions were:

- short-tail lums are noisy animals and active at night;
- the smell of short-tail lum faeces would be pervasive when the wind blew from that direction;
- the local abattoir with its unpleasant odour would increase operations;
- hectares of pristine countryside could possibly be destroyed if the mode of farming changed with a new permit;
- semi-domesticated lums would get out through the fences and mate with the remaining wild lums, weakening the genetic pool of the latter in this area;
- professional hunters would suffer further financial hardship through being in competition with lum farmers.

The application was refused by the Department of Primary Industries, Enterprise and Environment in the face of vigorous opposition.

Meanwhile, two species of flies and three species of beetles, which lay their eggs specifically in short-tail lum faeces or in the ground beneath them, were on their way to extinction in the region due to scarcity of lum faeces. A bird species and a lizard species that depend on these insects and their larvae for food also faced extinction. None of these animals had been studied and their decline towards extinction in the region was passing unnoticed. What didn't pass unnoticed resulted from the reduced numbers of one of the non-target mammals. Substantial numbers of this mammal, which preys on rodents, were incidentally shot and consequently populations of native rats began to expand rapidly due to reduced predator pressure. The rats' food became scarce in their natural environment and they began searching in new environments. Adjacent residential areas were inexplicably invaded by plagues of native rats.

1.6 DIVERSITY OF AQUACULTURE

Freshwater cyprinid fish and seaweeds dominate world aquaculture production. However, as well as these two large groups and the modest number of aquaculture species treated in this textbook, a huge diversity of species are cultured. FAO provides quantity and commercial value data on aquaculture production of some hundreds of species of fish, shellfish and algae that are cultured for human consumption and other uses. Even these three very broad categories of organisms do not encompass the whole range of aquacultured species. In addition to aquaculture for human consumption, there are international and local industries producing live feeds for hatcheries, e.g. dried brine shrimp cysts and live 'blood worms'. There is a huge worldwide aquaculture industry for ornamental fish, especially tropical freshwater and marine fish (Chapter 25). Other aquarium-related industries produce aquarium plants and freshwater and marine invertebrates, including coralline algae/coral-encrusted substrates ('living rock') for tropical marine aquaria. Pearls and sponges are cultured and sold for their traditional uses.

In particular, the Asian countries with large and traditional aquaculture industries are involved in culturing a wide diversity of species. Cen and Zhang (1998) indicate that at least 110 species (including introduced species) are cultured in China. These include freshwater and marine fish, marine shrimps, prawns, crabs, bivalves, gastropods, a variety of seaweeds, and special products such as sea cucumbers, sea urchins, bullfrogs and soft-shell turtles (Chapter 20). Aquaculturists in Taiwan have developed techniques for larval culture of more than 90 species of freshwater and marine fish (Liao *et al.*, 2001). In Japan in 1997, 284 hatcheries together produced fingerlings of 88 fish species (Fushimi, 2001). Fingerlings of 73 species, amounting to 168 million fingerlings, were released into the environment in stock enhancement programmes.

1.7 STOCK ENHANCEMENT

This raises another aspect of the diversity of aquaculture: links between aquaculture and fisheries. Stock enhancement of restricted freshwater environments for subsequent fishing (either recreational or commercial) is a standard procedure. Stock enhancement of marine populations in an attempt to improve fishery catches is an important aspect of Japanese aquaculture (Fig. 1.9). Stock enhancement of marine populations is also practised in Taiwan, and to a limited extent in countries such as Canada, France, Norway, the UK and the USA. Stock enhancement programmes with 'seed' from aquaculture involve predominantly fish, but they are also used for shellfish such as abalone, scallops and marine lobsters. These restocking programmes are not unequivocally successful and the best that can be shown for many is increasing fisheries that are approximately correlated with increasing input to the population of cultured 'seed' (Fig. 1.10). The results of stock enhancement programmes for heavily overfished abalone stocks in Japan illustrate the variable successes of restocking programmes (Hamasaki and

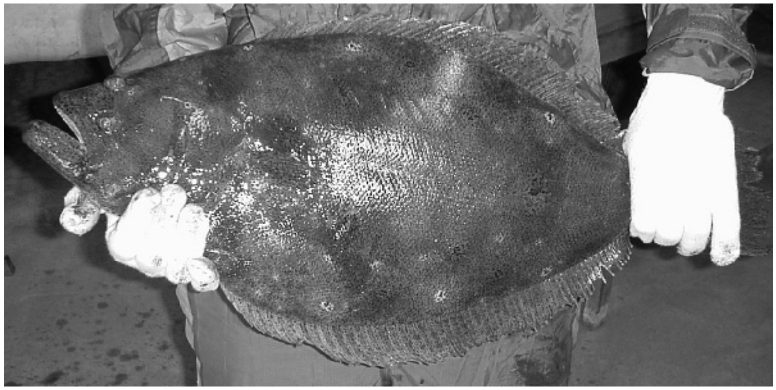

Fig. 1.9 Japanese flounder (*Paralichthyes olivaceus*) broodstock used to produce seed for stock enhancement (photograph by Dr Kotaro Kikuchi, Abiko Research Laboratory).

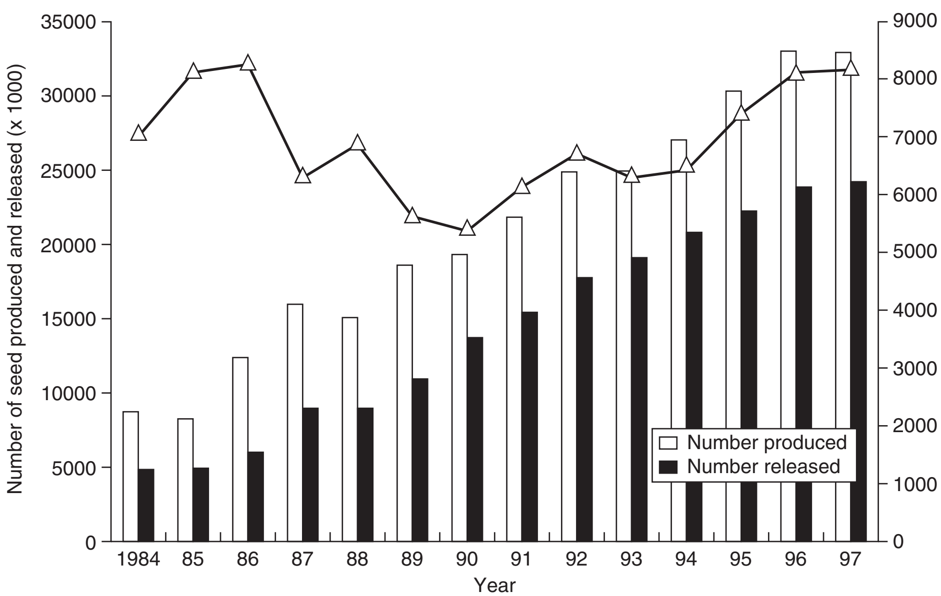

Fig. 1.10 Annual fluctuations in the catch of Japanese flounder (*Paralichthyes olivaceus*) versus 'seed' production and release in stock enhancement. Note upturn in declining fishery from 1990. Reprinted from Fushimi (2001) with permission from Elsevier Science.

Kitada, 2008). From surveys at 13 locations, the overall recapture rates ranged from 1.4 to 23.8%, the released abalone contributed from 6.9 to 83.5% of total catches, and the economic efficiency was estimated to range from 0.4 to 6.2. Economic efficiency is important in that it considers the increased value of the fishery from stock enhancement versus the hatchery costs of producing juveniles and seeding the fished populations (Hilborn, 1998). This variability in abalone restocking data was between locations in particular, but also between years of release. The abalone restocking programmes began in the late 1960s, but annual catches in Japan have declined from ca. 6500 tonnes in 1970 to 2000 tonnes in the mid-1990s (Hamasaki and Kitada, 2008).

Stock enhancement involves a more sophisticated approach than rearing large numbers of juveniles and releasing them into the vicinity of the fishery stock; other factors are very important in the success of the process (Le Vay *et al.*, 2007). These factors include genetic diversity of broodstock, sufficient habitat availability for the new releases, and the population dynamics and level of recruitment limitation of the fished stock. There is no point in stocking a fishery where there are inadequate habitats for new releases or where the fished stock is not limited by the level of natural recruitment. Conditioning and selection during culture in the hatchery may be a critical phase in maximising the physiological and behavioural fitness of juveniles after release.

1.8 NEW DEVELOPMENTS IN AQUACULTURE

Unlike animal husbandry, which is now based on a stable group of species, aquaculture is not stable in terms of the variety of species cultured and where they are cultured. As well as its rapid growth, this is an exciting aspect of aquaculture to consider what new developments will occur. For instance, bluefin tuna are very valuable and the southern and northern bluefin tuna fisheries are overfished to the extent that there is concern in some quarters that there are insufficient reproductive stocks for the populations to recover. Developing culture methods for these rapid-swimming oceanic fish that specifically feed on moving prey, and closing their life cycle in captivity, are two of the most challenging targets in aquaculture, but there is progress in techniques for culture on an experimental scale. There is potential for lucrative farming industries in the Southern and Northern hemispheres when commercial farming technology is developed. Two other valuable and very challenging animals to culture from eggs and to close the life cycle are spiny and rock lobsters, with their 8+ month plankton larval period (section 22.7), and freshwater eels, with their 10+ month planktonic period in the ocean (section 18.10.1). Both are currently caught for culturing after metamorphosis in the wild. Three 'holy grails' of aquaculture are to culture bluefin tuna and these lobsters and freshwater eels throughout their life cycles in captive conditions, removing the current reliance on capturing developing stages from the field, and giving the potential for genetic selection.

There are a number of other valuable species of marine fish for which the techniques of culture are in the early phases of development (Table 18.1). It is likely that some of these will become major aquaculture industries as the techniques required for commercial-scale farming are achieved.

1.8.1 Pangasid catfish

Pangasid catfish have joined the ranks of the major groups of fish species that are farmed (Figs 1.8, 1.11). The development and assessment of this industry is reviewed by Phuong and Oanh (2009). Vietnam is recorded as producing about 850 000 t/year and the sheer size of the industry is illustrated by the great number of staff processing fillets for one company (Fig. 1.12).

There are a number of pangasid species in the Mekong Delta rivers, and some were traditionally reared on a small scale. 'Basa' (Vietnamese name for *Pangasia bocourti*) was cultured in floating cages in the Delta (Phuong and Oanh, 2009).

Pangasid catfish have a number of favourable attributes for commercial aquaculture, and were 'waiting to be adopted', for the following reasons:

- Broodstock mature several times a year and can be strip spawned.
- Good numbers of large eggs are produced and hatchery techniques for rearing of eggs and larvae are relatively straightforward.
- Fingerlings grow rapidly in the hatchery to 3 cm when they may be transferred to farms for grow-out.
- There is rapid growth to market size, 2 kg, in 12 months.
- Farming techniques are inexpensive and straightforward: floating net cages, fenced enclosures and earthen ponds.
- They can be fed on inexpensive diets, such as rice bran and soybean meal.
- They tolerate low DO conditions.
- They are relatively disease free.

Fig. 1.11 *Pangasius hypophthalmus* catfish ('tra'). (Photograph by Karelj.)

Fig. 1.12 Workers trimming basa fillets. (Photograph courtesy of Vihn Hoan Corp.)

- There is good market acceptance: they can be processed to produce fillets of pale, mild and bone-free flesh, which can be prepared in a variety of ways.

However, there was insignificant production of these catfish until the mid-1990s (Fig. 1.13) and then phenomenal growth in the Mekong Delta of Vietnam when the favourable attributes of pangasid catfish for commercial aquaculture were realised (Phuong and Oanh, 2009). This growth came essentially from three developments:

- Establishing reliable hatchery and nursery methods in 2000, instead of being dependent on collecting seed stock from the wild was probably the key breakthrough.
- A move from pond, cage and pen modes of grow-out culture to focus on pond culture with 95% of total production coming from ponds in recent years and large farms having up to 26 ponds (Phuong and Oanh, 2009).
- Recognition of the economic potential of pangasid aquaculture by the Vietnamese government, which established supportive policies such as giving bank loans to

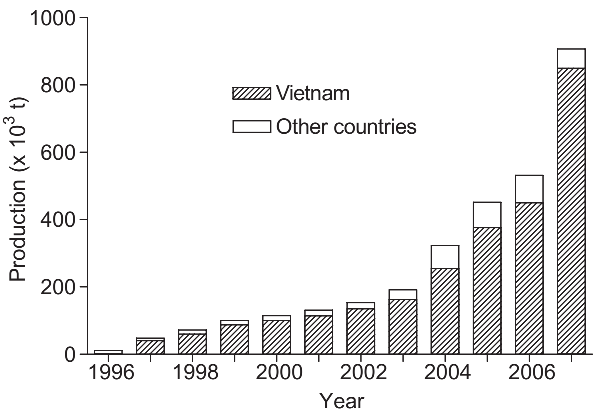

Fig. 1.13 Growth of pangasid catfish farming as production per year in Vietnam and in other countries.

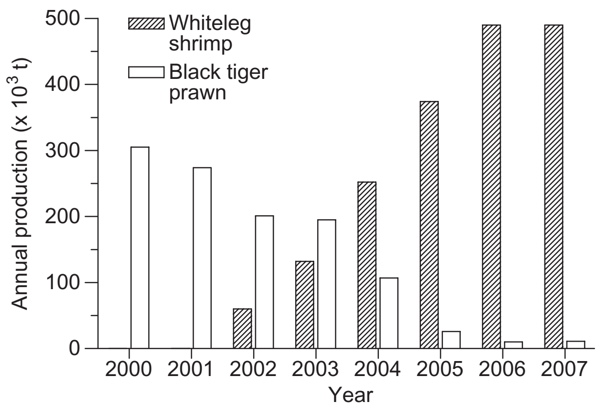

Fig. 1.14 Decline in annual production of black tiger (*Penaeus monodon*) and growth of whiteleg shrimp (*Litopenaeus vannamei*) production in Thailand from 2000 to 2007.

expand production and to improve processing infrastructure; providing technical training; and involving universities and other research organisations.

Post-harvest processing of the catfish is to international standards (Fig. 1.12) and production is mainly for export to a large number (ca. 80) and wide range of countries, to the chagrin of some local fishing and aquaculture industries. Vietnam has been accused of dumping in the USA and the catfish industry lobbied for a 39% tariff on pangasid catfish imports. The Vietnamese names 'basa' (*Pangasia bocourti*), and 'tra' (another commonly cultured species, *P. hypophthalmus*) (Fig. 1.11) are not good marketing names in some overseas countries (although used). Thus, a variety of other, more attractive, marketing names have been used, including 'sea sole', 'grouper', 'cream dory', 'white river cobbler' and 'white Mekong grouper'. Although the bulk of production is tra, it is regarded as having lesser flesh quality than basa. The latter attracts a high price and is sometimes given a different name where the market discriminates.

1.8.2 Whiteleg shrimp

In the initial decades of marine shrimp farming, the black tiger prawn (or giant tiger prawn), *Penaeus monodon*, was the preferred species[3]. In 2000, global production of *P. monodon* was 623194 t. Global production of whiteleg shrimp, *Litopenaeus vannamei*, was only 2310 t in that year. The relative amounts of these two species have since changed dramatically to 560 704 and 1884 061 t, respectively. Thailand, the major global producer of marine shrimp, is a case in point. The whiteleg shrimp was introduced into Thailand and other countries of Asia in the late 1990s. Thailand did not record production of any whiteleg shrimp until 2002 and then its production expanded while that of the black tiger declined precipitously (Fig. 1.14). Some advantages of *L. vannamei* are outlined in section 21.2.3.

[3]Members of the decapod family Penaeidae are general called 'shrimp' and they are identified as 'marine shrimp' in this book (Chapter 21); but, confusingly, the official name of some species, i.e. in statistical records, is 'prawn'.

1.9 CONCLUSIONS

Aquaculture continues to grow in importance for seafood production while fisheries production shows little change. Aquaculture's increase as a percentage of total seafood production seems to be exponential and it seems inevitable that it will become the major source of seafood in the not too distant future. In terms of growth in animal production, which is particularly important as a direct food source ('food fish'), there has been most increase in production of freshwater species. This growth is mainly in the low-value fish species such as carp and related species. There will continue to be most growth in the developing countries where the political and cultural environments are more conducive to new and expanding ventures in aquaculture. As well as future expansion in quantity and value of aquaculture products, it is likely that significant new industries will develop based on new species. The very rapid developments of pangasid aquaculture in Vietnam and of whiteleg shrimp aquaculture in Thailand are examples of the potential for new industries.

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