AQUACULTURE PRODUCTION SYSTEMS

Edited by James H. Tidwell

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Preface

Aquaculture. A simple word but a complex story. It's also a story of contradictions. In some ways aquaculture is very old, having been around in some regions for 4,000 to 5,000 years. However, as a major industry, and source food for mankind, it's been around only about fifty to sixty years. While aquaculture is an industry of several hundred species, the vast majority of production is dominated by less than ten. Also, unlike other livestock crops, we not only raise herbivores and omnivores but also carnivores and even filter feeders. It is a complex story indeed.

The idea for this book began in the 1990s. At Kentucky State University (KSU) aquaculture was initially entirely a research area. We received approval to teach our first course in 1991 and I developed Principles of Aquaculture as an experimental course. Gradually my colleagues and I at KSU developed additional courses to fill out a curriculum. In the Principles of Aquaculture course, I gave an overview of concepts, and then worked through a short but comprehensive overview of some major aquaculture species. However, the systems used to raise the fish were given a very cursory overview of one or two lectures. The more I thought about it the more it seemed to me that the aquaculturist's real job is to manage the environment, and that is the job of the production system. Wouldn't it be productive to develop another course that approached aquaculture not from the direction of the culture species, but from the direction of the culture system itself? The fact is that all species from shellfish to blue fin tuna have certain things they all need. Primary among them is a suitable water temperature, sufficient dissolved oxygen, and a way to remove or detoxify their waste products. The theme of this book is to explain how all of the different production systems we use provide these services, in many diverse ways.

To provide the best coverage of the subject, and a comprehensive explanation of each system, my job was to try to convince one of the most knowledgeable experts on each system to provide a chapter covering that system. To do this I tapped into a network of colleagues and friends, many of whom I had gotten to know during my years or while working with the World Aquaculture Society (WAS) in a number of different roles. If you go through the list of contributors, you will find that there are no less than six former WAS presidents contributing to the book.

The book is intended as a resource for students and researchers. Even within aquaculture there are individuals who know a tremendous amount about one system, but have had limited exposure to other systems. It is also intended as a resource for those outside of aquaculture who wish to understand the industry better. In two of my chapters I have tried to explain in simple terms the basic concepts of the different systems. I have also used extreme examples to help those from other professions appreciate just how hard our job can be with some aquatic species. Examples of non-aquaculture professionals that I hope can benefit from this book include entrepreneurs, investment bankers, feed and equipment salesmen, engineers, and environmentalists.

Environmental groups often use the broad term "aquaculture" when referring to issues related to one particular species or production system. They often paint with a very "broad brush." With a greater knowledge of the many different systems encompassed by this term, they might better understand aquaculture and all it represents. They might also better understand that the system they take issue with is only a very small portion of the larger aquaculture industry while their comments and criticisms negatively impact ALL parts of the industry. They might also become better able to appreciate the continuing efforts to improve the system's efficiencies and sustainability credentials. They can then come to understand that some of these systems are actually able to *improve* the environment by filtering out excess nutrients from whatever source.

A final theme of the book is a look ahead. What new types or combinations of systems might we see down the road? How will climate change affect aquaculture and its ability to provide increasing amounts of high quality protein to human populations, especially in regions of the world that need it the most?

I hope this text can serve as a resource for students and practitioners for many years to come and that it inspires them to develop new systems in the future. The Blue Revolution is really just beginning.

Jim Tidwell

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A first of many thanks goes to Ms. Leigh Anne Bright. Her organizational skills and keen eye as a reviewer/editor of all of the chapter manuscripts kept the project moving forward. Also, her patience in times of crisis kept me from losing mine. Thanks to Ms. Karla Johnson for typing, retyping, and re-retyping my chapters through their many stages of evolution, while keeping our other duties on track as well. My appreciation to Mr. Charles Weibel for his good-natured assistance with figures. He improved many and actually recreated several to ensure the best quality for publication. Thanks to Mr. Shawn Coyle for keeping more than his share of our research responsibilities on track while this project demanded a significant percentage of my attention. My appreciation to the faculty, staff, and students of the Division of Aquaculture at Kentucky State University for their support while this project came together. Many, many thanks to the contributors of the chapters in the book. They have endured hundreds of e-mails and requests with patience and quick responses. I appreciate their support, endurance, and perseverance. I also look back and thank my mentors and fellow students at Mississippi State University in years past who helped me develop a real devotion to this discipline that has not diminished. I thank my friends and colleagues in the World Aquaculture Society who have helped me appreciate how diverse and dynamic this industry is and will continue to be. Finally, I thank my family. This includes my big brother, Bill, who has shown a real interest in the project; my wife, Vicki; and my children, Will, Chandler, and Patrick, who have shared me, and have often helped me, with many aquaculture endeavors over the years.

Aquaculture Production Systems

Chapter 1

The Role of Aquaculture

James H. Tidwell and Geoff Allan

Fish represent both a vital contribution to the human food supply and an extremely important component of world trade. The trend in both of these areas is toward increasing importance. This chapter discusses the current status of seafood supply, world trade in fisheries products, and the relative contributions of aquaculture and capture fisheries. It addresses the question "Can we continue to meet the increasing global demand for seafood?"

1.1 Seafood demand

Fish is a vital component of the human food supply and man's most important source of high-quality animal protein. (As used here, the general term "fish" includes fish, mollusks, and crustaceans consumed by humans). It is estimated that worldwide about 1 billion people rely on fish as their primary source of animal protein (FAO 2001) and it provides more than 3 billion people with at least 15% of their average per capita animal protein intake (FAO 2009). It is a particularly important protein source in regions where high-quality protein from terrestrial livestock is relatively scarce. For example, in 2005, fish supplied less than 10% of animal protein consumed in North America and Europe (7.6%) but 19% of animal protein in Africa and 21% in Asia (FAO 2009).

Consumption of food fish is increasing, having risen from 40 million tonnes in 1970 to 86 million tonnes in 1998 (FAO 2001), and then to 115 million tonnes

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in 2008 (FAO 2010). Large increases in international meat prices in 2004 and 2005 continued to push consumers toward alternative protein sources, such as fish. Global per capita fish consumption has increased over the past four decades, rising from 9.0 kg/person in 1961 to an estimated 17.1 kg/person in 2008 (FAO 2010). Based on projected increases in consumption rates alone (assuming no increase in the human population) it is estimated that the demand for seafood will increase by more than 10 million tonnes per year by 2020 (Diana 2009). However, fish consumption is not distributed evenly. In 2008 Low Income Food Deficit Countries (LIFDCs) had a per capita fish consumption rate of 13.8 kg/person/year, which is about half that of industrialized countries (28.7 kg/person/year; FAO 2010). In Africa in 2007, per capita fish consumption was 8.5 kg, Latin America 9.2 kg, and Asian countries other than China, 14.6 kg. On the higher end, per capita consumption in 2007 averaged 22.2 kg in Europe, 25.2 kg in Oceania, 24.0 kg in North America, and 26.7 kg in China (FAO 2010).

How much seafood is consumed varies not only by region but also by the type of seafood. In northern Europe and North America demersal (bottom living) fish are preferred, while in Asia and the Mediterranean cephalopods, such as squid, are preferred. Crustaceans (like crabs and shrimp, which are relatively expensive) are mostly consumed in affluent economies. Of the 16.5 kg of fish products available for consumption per person worldwide in 2007, 12.8 kg (75%) were finfish, 1.6 kg were crustaceans and 2.5 kg were molluscs (FAO 2010). These figures represent an over three-fold increase in consumption of crustaceans and molluscs over the past forty years.

While increases in per capita consumption account for a small portion of the increase in total demand, it is the growing human population that is the main driving force for this steadily increasing demand for food fish. In fact, although the total amount of fish available for human consumption has increased, the supply per capita has remained at about the same levels as those in 2004 because the human population is growing at about the same rate as seafood supplies. The global population reached 6 billion in 1999 with predictions that it may exceed 9 billion by 2050 (Duarte *et al.* 2009). That figure is approaching the maximum human population that some research calculates the earth can sustain (Cohen 1995). Contributing to that conclusion are analyses that indicate that shortages in both food and water will constrain the growth of terrestrial agriculture in the future (Duarte *et al.* 2009). Disturbingly, most of the population growth is predicted to occur in less developed countries such as Asia, Africa, and South America.

1.2 Seafood supply

In 2008 the total world supply of fish was about 142 million tonnes (FAO 2010). Capture fisheries (inland and marine) produced about 90 million tonnes with about 80 million tonnes being from marine capture and a record 10 million tonnes being captured from freshwater (FAO 2010). Of this, about 27 million tonnes (roughly 19% of the total) was destined for nonfood uses, primarily as fish meal in animal feeds (20.8 million tonnes). The other 81% of total fishery production (115 million tonnes in 2008) was used for human food (FAO 2010).

Today, fish is the only important food source where a large portion is still gathered from the wild rather than produced from farming. While some marine and freshwater capture fisheries may have individual populations that could support additional exploitation, it appears unlikely that large increases from either of these sources will be forthcoming on a sustainable basis. For marine capture fisheries, FAO reports that in 2008 only 3% of the stock groups were under exploited and 12% were moderately exploited and could perhaps produce greater yields (FAO 2010). However, 53% were fully exploited, 28% overexploited, 3% depleted, and 1% were recovering from depletion (FAO 2010). This means that 85% of marine fisheries are biologically incapable of sustainably supporting increased yields (FAO 2010).

The FAO reports that the percentage of overexploited, depleted, and recovering stocks is consistently increasing. In fact, global marine capture fisheries production has been, at best, stagnant for over twenty-five years. The 80 million tonnes produced by global marine capture fisheries in 2008 is less than the 85 million tonnes produced in 1992 (FAO 2010). The maximum wild capture fisheries potential for the world's oceans has likely been reached. In fact, by some estimates, current ocean harvests may already be greater than levels considered sustainable (Coll *et al.* 2008) and it does not appear likely that we can turn to increased capture yields from freshwater. The FAO states that "globally, inland fishery resources appear to be continuing to decline as a result of habitat degradation and overfishing" and that this trend "is unlikely to be reversed" (FAO 2007).

As marine capture fisheries have become depleted and fish harder to catch, many fishermen and governments have responded with increased investment in equipment and technology. These changes have actually put increased pressure on wild-fish stocks. More efficient fishing technology also decreases the reproductive capacities of fisheries, thus exacerbating the effects of overharvesting. Based on the assessment of overexploitation of many fish stocks, and overcapacity and overcapitalization of many fishing fleets, by the mid 1970s it was widely concluded that many capture fisheries were not commercially viable without significant government subsidies (Mace 1997). The solution appeared to be to reduce the size of the fishing fleets. However, with advances in technology and increased mechanization, the ability of each remaining boat to catch fish (its "fishing power") increased. So while the number of fishers in industrialized countries has steadily declined, dropping 24% between 1990 and 2009 (FAO 2009), the pressure on the fish stocks largely has not decreased.

However, not all the news for capture fisheries is bad. Consistent increases in catches of certain species have been observed in the Northwest Atlantic and Northeast Pacific. These two regions are considered among the most regulated and managed in the world and this probably indicates that with proper management these fisheries can effectively continue producing significant levels of harvest without depleting the populations. However, in summary, there is widespread agreement that the supply from the wild, be it of freshwater or marine origin, is *not* likely to increase substantially in the future.

1.3 Seafood trade

Fish not only makes important contributions to food security but also has tremendous economic importance, being one of the most highly traded food and feed commodities globally. Total world exports of fish and fishery products reached a record value of US$85.9 billion in 2006 and are predicted to reach US$92 billion for 2007. This represents a 57% increase in exports since 1996 (FAO 2009). In 2008, 44.9 million people were directly engaged in primary production of fish either through fishing or aquaculture (FAO 2010). This represents a 167% increase since 1980 (16.7 million people; FAO 2010).

Table 1.1 lists the top-ten exporters and importers of fish and fish products in 1998 and 2008. In 2008 China was the world's largest exporter, shipping fish products valued at US$10.1 billion. This represents an almost four-fold increase in export values in ten years. However, the most *rapid* growth of the

Table 1.1 Top-ten exporters and importers of fish and fishery products in 1998 and 2008 in terms of value (USD) and annual rate of growth (APR; FAO 2010).

	1998	2008	APR (%)
	Millions (USD)		
EXPORTERS			
China	2,656	10,114	14.3
Norway	3,661	6,937	6.6
Thailand	4,031	6,532	4.9
Denmark	2,898	4,601	4.7
Vietnam	821	4,550	18.7
United States	2,400	4,463	6.4
Chile	1,598	3,831	8.4
Canada	2,266	3,706	5.0
Spain	1,529	3,465	8.5
Netherlands	1,364	3,394	9.5
TOP TEN SUBTOTAL	23,225	51,695	8.3
REST OF THE WORLD TOTAL	28,226	50,289	5.9
WORLD TOTAL	51,451	101,983	7.1
IMPORTERS			
Japan	12,827	14,947	1.5
United States	8,576	14,135	5.1
Spain	3,546	7,101	7.2
France	3,505	5,836	5.2
Italy	2,809	5,453	6.92
China	991	5,143	17.9
Germany	2,624	4,502	5.5
United Kingdom	2,384	4,220	5.9
Denmark	1,704	3,111	6.2
Republic of Korea	569	2,928	17.8
TOP TEN SUBTOTAL	39,534	67,377	5.5
REST OF THE WORLD TOTAL	15,517	39,750	9.9
WORLD TOTAL	55,051	107,128	6.9

period actually occurred in Vietnam, whose exports increased 450% over the same ten-year period. Between 2006 and 2008 Vietnam moved from eighth to fifth on the list of top exporters. On the import side, Japan has remained the world's largest importer of fish products for twenty-five years, importing approximately US$15 billion per year. However, Japan's rate of increase has slowed in recent years, increasing only US$500 million from 1998 to 2008. The second largest importer has historically been the United States, whose imports increased US$5.5 billion during the same period, and who will likely overtake Japan as the world's top importer (ARUSSI 2009). Paradoxically, despite being the world's largest *exporter,* China also had the most rapid increase in *imports* during this period, with a 420% increase in value between 1998 and 2008 (FAO 2010). It is predicted by some that China will actually become a net *importer* of fish and fish products in coming years as per capita incomes there continue to rise. South Korea also showed substantial increases, with a greater than 400% increase in imports over the ten-year period.

Fish products are extremely important to the economies of many countries, and the past four decades have seen major changes in the geographical patterns of the fish trade, much of it benefiting the developing world. In 1976, developing countries accounted for approximately 37% of fisheries exports. By 2008, developing countries were responsible for about 50% of exports (FAO 2010). These changes are further supported by the fact that developing countries had a trade surplus of US$4.6 billion in 1984 which grew to US$24.6 billion in 2006, a 434% increase in just over twenty years (FAO 2009). This is a much faster increase than we see in other agricultural commodities such as rice, tea, or coffee. The poorest countries (Low Income Food Deficit Countries, or LIFDCs) have also shown considerable growth in exports accounting for 20% of fishery exports in 2006 with a trade surplus of US$10.7 billion (FAO 2009).

Another major trend that is occurring is in *what* is being traded. In the past, developing countries exported raw materials that were then processed into value-added product forms in developed countries. Increasingly, the processed or value-added products are being generated *within* the developing country for export, capitalizing on low labor and operating costs. This is often done with processing infrastructure developed with outside investments from developed countries. The quantity of fish exported by developing countries for human consumption increased from 46% in 1998 to 55% in 2008 (FAO 2010).

However, an important share of the exports of developing countries is still in lower value nonfood products. A large portion of this is in the form of fish meal, destined for use as a feed ingredient or fertilizer. In 2008, of the fish products exported by developing countries, fish meal represented 36% by quantity but only 5% by value.

1.4 Status of aquaculture

As we have shown, the demand for food fish increases each year. As we have also shown, the supply from wild harvest is not expected to increase substantially

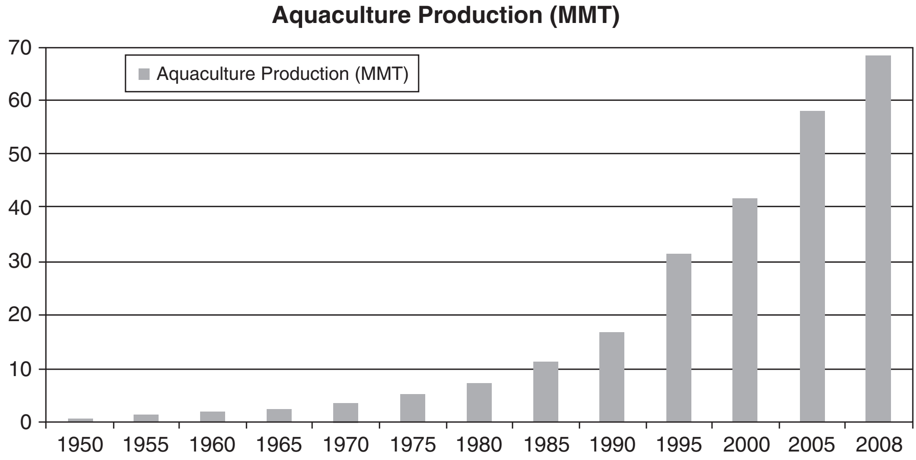

Figure 1.1 Annual world aquaculture production (in million tonnes) since 1950.

in the future. The only other source for the human population to produce food fish is aquaculture and global aquaculture growth has been extraordinary (fig. 1.1). Aquaculture production was only 1 million tonnes in the 1950s (FAO 2007). In the 1970s aquaculture contributed less than 4% of total seafood production. However, by 1997 aquaculture contributed about 27% of the food fish supply, by 2004 it contributed 32%, and by 2008 it contributed more than 47% (fig. 1.2). By 2015, aquaculture will pass capture fisheries as the leading source of food fish for the human population and the proportion contributed by aquaculture will continue to increase each year thereafter (Lowther 2007).

Aquaculture is growing more rapidly than any other animal food-producing sector, with an annual growth rate of 6.6% since 1970 (FAO 2010). This is contrasted with a growth of only 1.2% for capture fisheries and 2.8% for terrestrial farmed meat production over the same period (fig. 1.3). It is estimated that

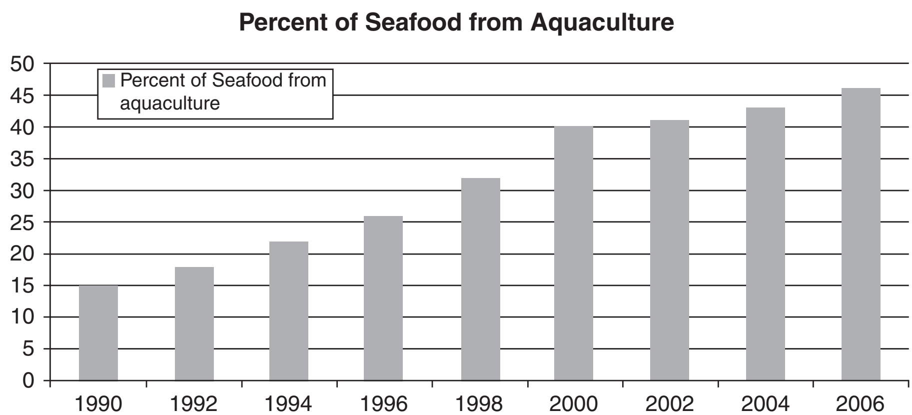

Figure 1.2 Aquaculture production as a percentage of total seafood supply.

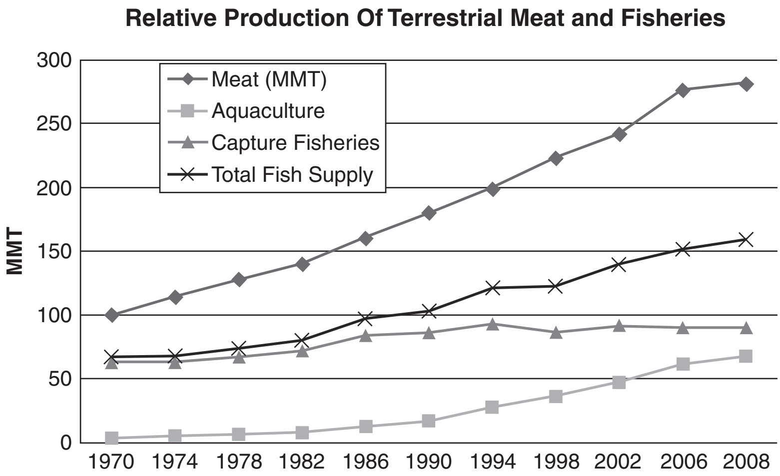

Figure 1.3 Relative production of terrestrial meat production, total seafood supply, capture fisheries, and aquaculture (in million tonnes).

the land devoted to row crop and grazing will have to increase by 50 to 70% by 2050 to meet food requirements for the projected increases in the human population (Molden 2007). However, the amount of land devoted to terrestrial crop production actually decreased from 0.5 ha/person to 0.25 ha/per person during the period 1960 to 2000 (Molden 2007). Extrapolation of population growth estimates and estimates of the availability of cultivable lands create "a likely scenario in which Earth's capacity to support the human population may be reached within the next decades, at population levels below currently proposed estimates" (Duarte *et al.* 2009). This raises the real question—can the human population feed itself in the coming decades?

These conditions only bolster the case that a prudent development of aquaculture is essential. In 2008 total aquaculture production (including plants) was reported to be 68.3 million tonnes with a value of US$106 billion, of which 53 million tonnes was for food fish with a value of US$98.4 billion (FAO 2010). It is anticipated that to keep pace with demand, aquaculture production of food fish will need to increase to 85 million tonnes (more than 75% growth) in the next twenty years (Subasinghe 2007).

So where is aquaculture production occurring? Currently, Asia dominates production. In 2009, Asia accounted for 89% of world aquaculture production by quantity and 79% by value (FAO 2010). China alone produces more than 62% of the world's aquaculture volume and 51% by value (FAO 2010). Of the top-ten countries in aquaculture production in 2006, only two (Chile and Norway) are not in the Asian region and they account for less than 3% of world production (table 1.2). However, as illustrated by table 1.3, there are very rapid increases in production occurring in some countries outside of Asia.

Aquaculture is extremely varied in terms of what species are raised. Based on tonnage, if we include aquatic plants, the individual species with the highest

Table 1.2 Top-ten aquaculture producers of food fish supply in 2008 in quantity and growth.

	2000	2008	APR (%)
	Thousand Tonnes		
China	21,522	32,736	5.4
India	1,943	3,479	7.1
Vietnam	499	2,462	16.4
Indonesia	789	1,690	7.0
Thailand	738	1,374	8.1
Bangladesh	657	1,006	5.5
Norway	491	844	7.0
Chile	392	843	10.1
Philippines	394	741	8.2
Japan	763	732	0.5

Note: Data exclude aquatic plants.

aquaculture production in 2005 was the Japanese kelp (*Laminaria japonica*) at 4.9 million tonnes followed by the Pacific cupped oyster (*Gassostrea gigas*) at 4.5 million tonnes (Lowther 2007), silver carp (*Hypopthal michthys molitrix*) at 4.0 million tonnes, grass carp (*Ctenopharyngodon idellus*) at 3.9 million tonnes, and common carp (*Cyprinus carpio*) at 3.4 million tonnes (FAO 2007). Bighead carp (*H. nobilis*) and crucian carp (*Carassius carassius*) also exceeded 2 million tonnes (Lowther 2007).

If we look at value-based species groups as defined by FAO, the highest reported values were for carps (US$18.2 billion), followed by shrimp and prawns (US$10.6 billion; Lowther 2007) and salmonids (US$7.6 billion). While crustaceans (such as shrimp) rank fourth in terms of quantity produced, they rank second in terms of total value, reflecting their relatively high selling prices. In fact, aquaculture production of shrimp increased 165% from 1997 to 2004, driving

Table 1.3 Top-ten aquaculture producers ranked in terms of their annual percentage rates (APR) of growth over a two-year period.

	2004	2006	APR (%)
	Tonnes		
Uganda	5,539	32,392	141.83
Guatemala	4,908	16,293	82.20
Mozambique	446	1,174	62.24
Malawi	733	1,500	43.05
Togo	1,525	3,020	40.72
Nigeria	43,950	84,578	38.72
Cambodia	20,675	34,200	28.61
Pakistan	76,653	121,825	26.07
Singapore	5,406	8,573	25.93
Mexico	104,354	158,642	23.30

supply up but prices down. The highest reported value for a single species was US$5.9 billion for the Pacific white shrimp (*Litopenaeus vannamei*) followed by the Atlantic salmon (*Salmo salar;* Lowther 2007).

Compared to terrestrial agriculture, aquaculture is extremely diverse with over 449 species of plants and animals being raised (Duarte *et al.* 2009). Production trends indicate that the diversity of species being produced in aquaculture is still on the increase. Duarte *et al.* (2009) estimated that the number of species being cultured increases 3% per year. Some of these new species groups have shown very large increases in production. Examples include sea urchins and echinoderms (4,833% increase), abalones, winkles, conchs (884%), and frogs and other amphibians (400%) in only a two-year period (2002 to 2004). However, a few species dominate production with the top-five species accounting for 62% of total aquaculture production and the top-ten species accounting for 87% (FAO 2007).

Aquaculture also varies by environment, utilizing marine, freshwater, and brackish water environments. When considered in terms of total weight, in 2005 mariculture accounted for approximately 51% of production while freshwater accounted for 43% (FAO 2007). However, these values include a substantial tonnage of aquatic plants, which are primarily produced in marine systems. When we look specifically at food animal production, freshwater becomes more important, accounting for 60% of production by quantity (fig. 1.4) and 48% by value (fig. 1.5), compared to 32% and 31%, respectively for mariculture and 8% and 13%, respectively for brackish water (FAO 2009).

Worldwide in 2008, freshwater fishes were the dominant group (table 1.4) in terms of productions (28.8 million tonnes) and most of this is composed of different species of carps (FAO 2010). In fact, carps accounted for approximately

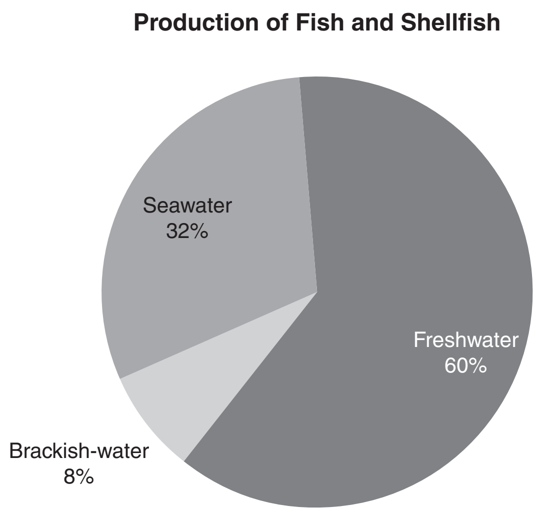

Figure 1.4 Percentage by weight of edible fish and shellfish products produced in freshwater, seawater, or brackish water.

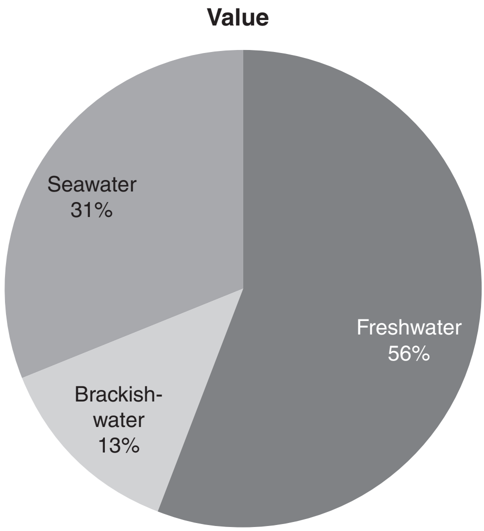

Figure 1.5 Percentage by value of edible fish and shellfish products produced in freshwater, seawater, or brackish water.

71% of all freshwater fish production (FAO 2010). A snapshot of global aquaculture in 2008 shows that over one half of its production (55%) was freshwater finfish with a value of US$40.5 billion. The next largest group was molluscs at 25% of total production worth US$13 billion. Crustaceans accounted for 9.5% of total aquaculture production by weight, but 23% by value. Like crustaceans, the relative value of marine fish is quite high representing only 3% of global aquaculture production but 7% of value (FAO 2009).

1.5 Production systems

Although data on production systems are not yet widely tracked, it would be safe to say that the majority of fish and crustaceans produced for food by aquaculture are currently raised in ponds. In China in 2008, 70.4% of freshwater aquaculture

Table 1.4 World aquaculture production: major species groups[1] by percent of total quantity and total value in 2006 (FAO 2010).

Species Groups	Quantity (%)	Value (%)
Freshwater fishes	54.7	41.2
Mollusks	24.9	13.3
Crustaceans	9.5	23.1
Diadromous fishes	6.3	13.3
Marine fishes	3.4	6.7
Aquatic animals—NEI[2]	1.2	2.4

[1] Does not include plants.
[2] NEI = not otherwise included.