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

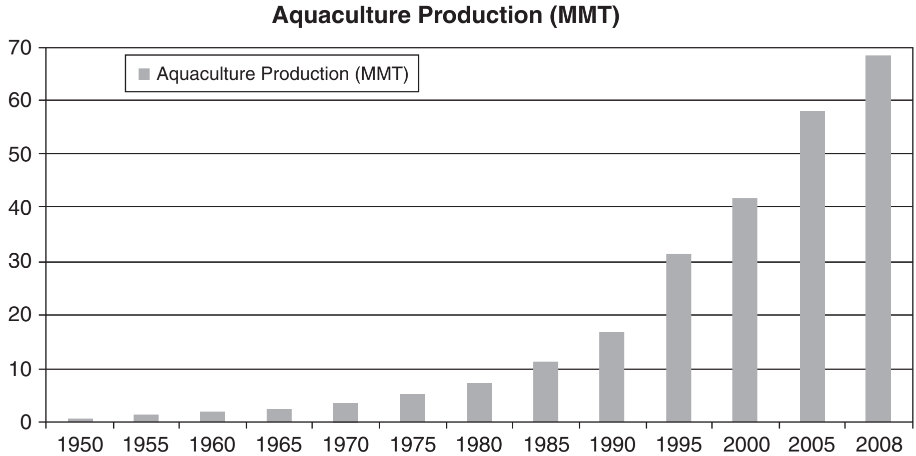

Figure 1.1 Annual world aquaculture production (in million tonnes) since 1950.

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

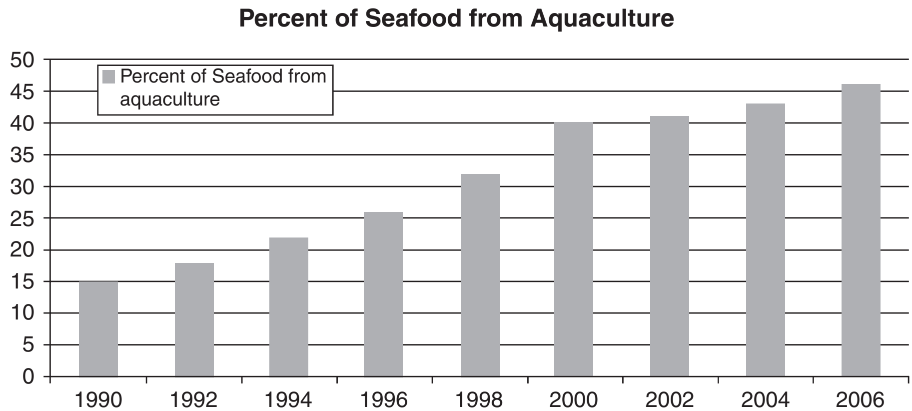

Figure 1.2 Aquaculture production as a percentage of total seafood supply.

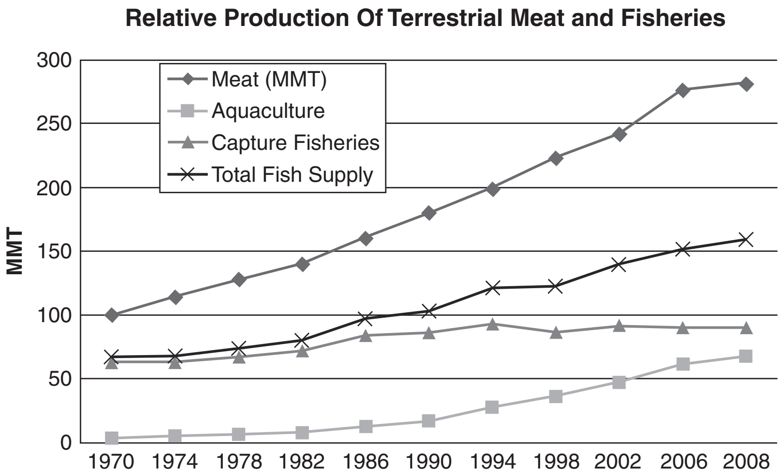

Figure 1.3 Relative production of terrestrial meat production, total seafood supply, capture fisheries, and aquaculture (in million tonnes).

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

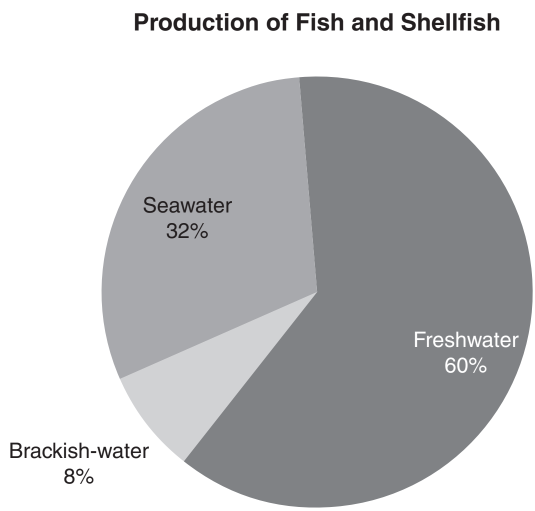

Figure 1.4 Percentage by weight of edible fish and shellfish products produced in freshwater, seawater, or brackish water.

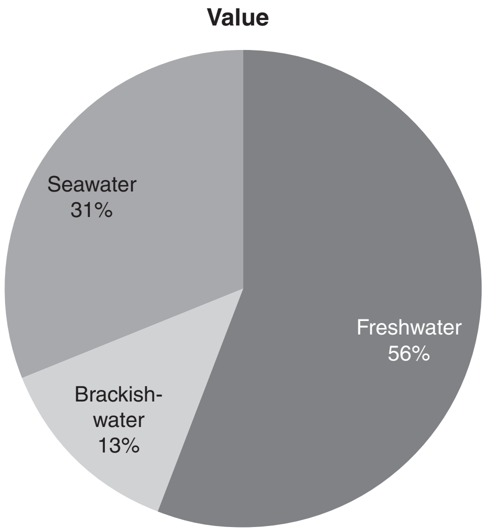

Figure 1.5 Percentage by value of edible fish and shellfish products produced in freshwater, seawater, or brackish water.

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.

relied on ponds, with 11.7% conducted in reservoirs, 7.7% in natural lakes, 5.6% in rice paddies, 2.7% in canals, and 2.6% in other systems (FAO 2010).

1.6 The future and the challenge

As we have seen, the demand for fish increases each year. Per capita consumption shows slight increases but the more important factor is continuing population growth. It is estimated that to even maintain the current level of per capita consumption, the fish supply will have to almost double in the next twenty years. That translates into almost 40 million tonnes of additional supply per year. As discussed, it is unlikely that significant increases in wild harvests will occur. So where will this additional fish come from? There is only one answer. It has to come from aquaculture.

As we can see, aquaculture is no longer just a promising line of research or a promising theory. As Melba Reantso of FAO described it, "aquaculture is now known as the emerging new agriculture, the catalyst of the 'blue revolution,' the answer to the world's future fish supply, the fastest food producing sector, the future of fisheries." Still, the task ahead is daunting. Aquaculture is expected to supply global seafood security, nutritional well-being, poverty reduction, and economic development by meeting all of these demands, but also accomplishing this with a minimum impact on the environment and maximum benefit to society. The remainder of this book will be devoted to helping the reader follow the development of aquaculture over time, truly understand and appreciate how the diverse systems used to raise these aquatic animals operate, and grasp the evolution of new systems and the changes that are sure to be wrought by climate change.

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Chapter 2

History of Aquaculture

Robert R. Stickney and Granvil D. Treece

For purposes of this historical account the concentration is on finfish, shrimp, and mollusks that are reared as food for human consumption. The reader should be aware that aquaculture is much more expansive. In the finfish category alone there is a considerable amount of culture of ornamental fishes, particularly freshwater species. There is also a good deal of interest in marine ornamentals but the number of species that have been successfully cultured is considerably smaller than is the case for their freshwater counterparts. In some parts of the world there is also aquaculture of baitfish, such as minnows, for marketing to the recreational fishing community.

There are a large number of mollusks, crustaceans, and other invertebrate groups that include species currently being produced in aquaculture. Oysters, clams, mussels, and abalone are examples of mollusks being cultured, while various species of marine shrimp and one species of freshwater shrimp, *Macrobrachium rosenbergii,* are the most important groups of crustaceans being cultured for the human food market. Crabs are also cultured to a limited extent, and there is some culture of lobster. There is also some culture of sea urchins and sea cucumbers as well as a few other invertebrates.

Captive spawning and rearing of fingerlings for stocking recreational fishing waters has a relatively long history. The foundations upon which the science of aquaculture are based can be traced in large part to the pioneering fish culturists who developed the various processes associated with spawning and rearing a variety of both marine and freshwater fishes. Fish continue to be produced

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Aquaculture Production Systems, First Edition. Edited by James Tidwell.

for recreational purposes but there are also hatcheries producing fish in many countries to enhance wild capture fisheries. Japan has a history over the past several years of also producing shrimp for enhancement stocking.

Ocean ranching is another form of aquaculture. It most commonly involves salmon that are released from hatcheries as smolts to find their way to the ocean where they grow to maturity and then return to their natal waters to spawn. Some of the returning fish are used as broodstock, with the majority being taken by commercial fishermen. In Japan, a modified form of ocean ranching has been developed with non-salmonid marine fishes. Young fish are trained in the hatchery to respond to a sound source at feeding time. Once the behavior is ingrained in the fish, they are released into the wild near a feeding station that emits the same sound that had been used for conditioning. Feeding continues using the sound attractant until the fish reach market size, after which they are captured for processing.

A variety of invertebrates are cultured as food for other cultured species. Examples are brine shrimp, rotifers, and copepods. Various species of phytoplanktonic algae are cultured as food for those invertebrates, thus requiring the aquaculturists to maintain at least three different culture systems: phytoplankton, zooplankton, and the fish or invertebrate species that will ultimately be marketed.

Phytoplanktonic species are not the only members of the plant kingdom that are being cultured. Macroscopic algae are also of interest to aquaculturists. For example, nori is used to make sushi wrappers and is also used in other products that are consumed by people. A few higher plants, such as water chestnuts, are also cultured for human consumption.

In most cases invertebrates and aquatic plants have a long history of consumption by humans but a relatively short history of being cultured. Most of that culture activity began in the twentieth century. One notable exception is oysters, which were apparently cultured during the days of the Roman Empire nearly 2,000 years ago (Beveridge & Little 2002).

Hydroponics is another form of aquaculture in which terrestrial plants are grown in nutrient-enriched water. Various vegetables can be grown hydroponically and the approach has been used in conjunction with fish or invertebrate aquaculture in polyculture.

2.1 Beginnings of aquaculture

The dawn of aquaculture is shrouded in mystery, although most who have delved into that history agree that the art of aquaculture began in China. Various authors have indicated that the beginnings of aquaculture can be traced as far back as 3,500 to 4,000 years Before Present Era (BPE). Among them were Hickling (1962, 1968), Rabanal (1988), Bardach *et al.* (1972), and Ling (1977). Jessé & Casey undated posited that aquaculture may go as far back as 5,000 years BPE. The latter indicated that pond culture of grey mullet (*Mugil cephalus*) and carp (presumably common carp, *Cyprinus carpio*) began with the first of China's

Emperors in the period from 2852 to 2737 BPE, but provided no details on the source of that information. Ling (1977) indicated that carp culture developed from simply catching and holding fish in baskets to holding them in traps and finally, feeding them to grow them to larger sizes before harvesting.

While the precise period when aquaculture developed in China may be in question, there is general agreement that the first published work on the subject was a small volume by Fan Li that appeared about 475 BPE (for example, see Borgese 1980). Ling (1977) indicated that Fan Lee described how to spawn fish including how to select ripe brooders. Pillay & Kutty (2005) indicated that Fan Li was a politician turned fish culturist and that he made his fortune growing fish. Other early Chinese publications on collecting carp fry from rivers and rearing them in ponds were also produced according to Pillay & Kutty (2005).

Ling (1977) reported that when the Lee Dynasty was founded in 618 BPE, a thousand years or more of common carp culture was threatened. That was because the word Lee is pronounced the same as lee, which was the word used for carp. It was considered sacrilege to catch and eat lee because it was an insult to the Emperor. To get around the problem, culture methods for grass (*Ctenopharyngodon idella*), silver (*Hypophthalmichthys molitirix*), bighead (*Aristichthys nobilis*), and mud carp (*Cirrhinus molitorella*) were developed, which led to polyculture.

If one follows the chronology of aquaculture development produced by Jessé & Casey undated, the Egyptians may have developed some form of aquaculture at about the same time as the Chinese. Those authors attribute Egyptian hieroglyphics that appear to show pond culture being developed between 2357 and 1786 BPE. Another source places the Egyptians practicing intensive fish culture during the period 2052 to 1786 BPE, corresponding with the Middle Kingdom period (Anonymous, undated). In addition to reports of hieroglyphics depicting fish culture, a bas relief from the tomb of Thebaine, an Egyptian nobleman, depicts some type of tilapia being fished from an artificial pond (Chimits 1957). That bas relief was redrawn and also mentioned by Beveridge & Little (2002) as well as Pillay & Kutty (2005). Another bas relief from around 2500 BPE was reproduced in a book by Maar *et al.* (1966) that shows a pond with a variety of fish, at least one of which appears to be tilapia.

2.2 Expansion prior to the mid-1800s

Common carp culture was introduced from China to various parts of Southeast Asia by Chinese immigrants (Ling 1977). Carp appear to have been raised in ponds in Japan at least 1900 years ago (Drews 1951). However, fish culture was not important in Japan before the seventeenth century.

The Romans reportedly introduced carp from Asia Minor into Greece and Italy (Maar *et al.* 1966). The Romans also appear to have introduced common carp culture to England during the first century BPE (Beveridge & Little 2002). Carp culture was said by the same authors to have been established in central Europe by the seventh century. Pillay & Kutty (2005) indicated that carp culture was initiated when the fish were introduced to monastery ponds which occurred in the Middle Ages in western and central Europe (Beveridge & Little 2002). Over the centuries carp culture expanded throughout much of Europe. Today, the culture of various species of carp accounts for about 80% of the aquaculture production from marine and freshwaters in central and Eastern Europe (Szücs *et al.* 2007). Worldwide, carp and other cyprinids clearly dominate world production with respect to weight of cultured finfish produced (FAO 2006), with most of that production taking place in China.

Carp culture appears to have been conducted on at least part of the Indian subcontinent since the eleventh century (Pillay & Kutty 2005). The tradition in India has always been to culture the local carp species catla (*Catla catla*), rohu (*Labeo rohita*), and mrigal (*Cirrhinus mrigala*).

Brackishwater aquaculture in Southeast Asia reportedly began during the fifteenth century, probably in Indonesia (Pillay & Kutty 2005). Milkfish were produced at that time in coastal ponds called tambaks. Milkfish culture expanded to other parts of Southeast Asia including the Philippines and Malaysia, which continue to be major producing nations. Mullet also were probably produced in Southeast Asia 1400 years BPE (Ling 1977). Pillay & Kutty (2005) placed the origins of walking catfish (*Clarias* spp.) culture in Cambodia.

Native Hawaiians had been growing fish in ponds for as long as 500 years before the Hawaiian Islands were discovered by Captain James Cook in 1778. The Hawaiians would allow seawater to enter their ponds with the rising tide, then block off the pond entrances thereby trapping whatever creatures were present. The animals would then be allowed to grow to harvest size (Costa-Pierce 2002).

Trout were among the early groups of fishes to be cultured in Europe. Davis (1956) attributed the first successful artificial insemination of trout eggs to a monk in France who lived in the fourteenth century. Over the centuries, trout culture spread across much Europe and, ultimately, around the world. The European brown trout (*Salmo trutta*) was the subject of the early activity, though rainbow trout (*Oncorhynchus mykiss*) introduced from North America ultimately became more popular with fish culturists. The British introduced trout to some of their colonies in Asia and Africa mainly for recreational fishing (Pillay & Kutty 2005).

2.3 The explosion of hatcheries

While fish culture expanded over the centuries that followed the middle ages, that expansion was largely restricted to a small number of species and often depended largely on the capture of wild fry or fingerlings that were then confined for growout. Milkfish is an excellent example and that industry still relies largely on wild captured fry.

In the latter half of the nineteenth century, enthusiasm for recreational fishing coupled with increasing numbers of reports that many freshwater and marine stocks were being negatively impacted by overfishing, led to the development

Figure 2.1 State of Oregon railroad car used to transport fish.

of private and public hatcheries in Europe and North America. In the United States the initiative began when several states in the northeast established fish commissions that were charged with managing their fisheries. Some of the commissions turned to stocking as a means of enhancing their recreational fisheries. In most cases they initially turned to private fish producers to supply the fish, most commonly brook trout (*Salvelinus fontinalis*).

In 1872, the United States Commission on Fish and Fisheries was established by Congress and Spencer F. Baird, who conceived the idea and was named the first Commissioner. Baird was concerned about declining fish populations and directed a lot of the activity of the Commission toward developing hatcheries for both freshwater and marine species. As a result, over a period of several decades billions of eggs were hatched and their fry were distributed by the United States Commission on Fish and Fisheries, which later became the United States Bureau of Fisheries, Bureau of Commercial Fisheries, and, ultimately, the National Marine Fisheries Service (Stickney 1996a–e, 1997a–c). Millions of railroad miles passed under the wheels of cars hauling fish, first by the United States Commission and soon followed by state fish commissions or fisheries agencies (fig. 2.1). Hatcheries on the east coast produced Atlantic salmon (*Salmo salar*) for shipment to the west coast and hatcheries on the west coast (initially in northern California and later in Oregon and Washington) produced Pacific coho (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*) for shipment to the east. While no survival of salmon appears to have occurred in either case, hundreds of millions of eggs and fry were involved in the effort. This may be due to the natural tendency of smolts would be to turn the wrong direction if they survived long enough to reach the sea. It wasn't only salmon that were involved in the transfers. There were also largemouth bass (*Micropterus salmoides*), walleye (*Stizostedion vitreum vitreum*), cod (*Gadus morhua*), rainbow trout, and striped bass (*Morone saxatilis*), to name but a few. Striped bass from the east became established in California and continue to thrive there. Baird's successors continued to expand the numbers of hatcheries and species produced. Baird himself promoted the introduction of common carp into United States waters perhaps thinking that many of the European immigrants who made up a large percentage of the population at the time would have a preference for a species from their native countries with which they were familiar. The Commission stocked carp around the nation and territories but discontinued the process after only a few years because the waters were soon teeming with reproducing populations. Ultimately, carp were seen by most Americans as trash fish and their introduction is not generally considered to be one of Baird's crowning achievements.

Of the billions or perhaps trillions of eggs and larvae of marine species and some freshwater species that were stocked during the 1800s, there is little or no evidence of survival. The fish culturists of the late nineteenth and much of the twentieth century were unsuccessful in finding ways to feed the very tiny fry that are so common among marine species and the animals were typically released before their digestive systems were developed. The same was true for freshwater fishes with small eggs. Salmon and trout were exceptions in that they had large eggs and fry that survived on a yolk sac for an extended period following hatching. When they did begin exogenous feeding, the fry were more advanced and it was possible to successfully provide them with food of one kind or another—chicken egg yolk being one popular item. Details of this fascinating period of fish culture development in the United States can be found in a book by Stickney (1996a).

2.4 Art becomes science

It wasn't until the mid-twentieth century that the art of aquaculture developed into what exists today as a complex multidisciplinary science that now features over 200 species under culture (including invertebrates as well as finfish). However, significant progress in the development of the techniques required to spawn and rear a variety of species had been developed by the end of the nineteenth century as detailed by Bowers (1900). In fact, if one compares a hatchery from the late nineteenth century with one of today and overlooks modern materials such as fiberglass, PVC plumbing, electric pumps, and all sorts of electronic gadgets and just looks at the basics, it is not difficult to imagine that someone from the time of Spencer F. Baird would recognize a lot of what he would see. An earthen pond is still a pond. The linear wooden raceways of old are now fabricated of concrete, fiberglass, or aluminum and in many instances circular raceways have replaced linear ones, but the concept has not changed. I can see a Livingston Stone (who developed salmon and trout hatcheries in California in the 1870s) as finding himself right at home as soon as he learned how to use a dissolved oxygen meter and become adjusted to a few other gadgets that didn't exist in his time.

It is not possible to put a precise date as to when the art became science as it was an evolutionary process. Each hatchery manager probably developed some new techniques and those were shared among peers at meetings such as those of the American Fish Culturists Association, which was established in 1870 and later became the American Fisheries Society.

In the United States, university courses associated with fish culture were rare before 1950, and any that existed would have undoubtedly focused on techniques associated with the culture of species for stocking, which would mean almost exclusively salmonids and non-salmonid freshwater species. The University of Washington in Seattle, Washington, established a position in fish culture in 1920 (Stickney 1989). Lauren Donaldson, who took a position at the university in 1932, constructed a salmon return pond on the campus and established a salmon run. Salmon were literally returning to the classroom.

Ichthyologic research was being conducted at many universities in the early twentieth century but the focus was usually not on aiding in the development of fish culture. It is probably safe to say that most of the applied fish culture research that was being conducted took place in government hatcheries where the methodology was probably of the trial and error variety. Since the approach involved producing fry and fingerlings for stocking public waters, there was not a great deal of interest by the government hatcheries in developing the technology associated with growout to foodfish size. Those relatively few private foodfish producers were largely on their own.

Today aquaculture courses (which typically include fish culture, but are usually not restricted to the study of finfishes) can be found at colleges and universities across the world. Certificate, undergraduate, and graduate programs abound. A quick search for "aquaculture institutions" on the Internet will provide page after page of hits.

While Hickling (1962, 1968) authored short books on fish farming, there was no comprehensive treatment of global aquaculture available until the classic book by Bardach *et al.* (1972) appeared. That work was based on the information gathered by the two senior authors who traveled the world looking at the status of aquaculture. The book provides good documentation of the state of the art that existed early in the third quarter of the twentieth century. Much of the aquaculture at the time was artisanal in developing countries, and artisanal aquaculture continues to provide much of the fish available to local communities in developing nations today (fig. 2.2).

Much of the published information on fish culture prior to the 1970s consisted of gray literature and in such government publications as *The Progressive Fish-Culturist*, which was published by the United States government for many years before being taken over by the American Fisheries Society. That publication is now being published as *The North American Journal of Aquaculture*.

The growth of information on commercial fish culture over the past few decades has been exponential. A large number of journals dedicated to

Figure 2.2 Artisanal tilapia pond in the Philippines (Photo by Robert R. Stickney).

aquaculture in the broad sense, fish culture, or one of the many aquaculture subdisciplines—nutrition, disease, engineering, genetics and water quality to name a few—have been established and the list continues to grow. Similarly, books on aquaculture and the various specialized branches of the field have proliferated.

The number of societies that are solely focused on aquaculture or include aquaculture within the broader context of fisheries and/or aquatic sciences has also expanded. The formation of the World Mariculture Society in 1969 (the name was changed to the World Aquaculture Society in 1986) was seen by some observers as an audacious move. How dare a small group of Americans (and one individual from Great Britain) gathered in the state of Mississippi have the gall to create a global organization? While initiated by a group of about forty, the society has thrived and came to live up to its name. It has been joined by a number of other regional or national societies (e.g., the European Aquaculture Society) and chapters, meetings of which often attract over 1,000 attendees. Virtually all of these associations or groups also publish a magazine or newsletter, many produce published proceedings of their meetings, and some also have developed book series. Such organizations typically have members or at least attendees at meetings from academia and government agencies as well as from the commercial production and supply sectors.

Specialty organizations that focus on a particular area of interest have also been formed. Examples are organizations devoted to the culture of channel catfish, tilapia, trout, salmon, engineering, and economics.

2.5 Commercial finfish species development

Commercial finfish culture was limited in the United States until rapid development began in the 1960s. Initially, species selection was often based upon local interest and availability (e.g., channel catfish, trout) but in many cases was also driven by declines in wild fisheries (e.g., Atlantic salmon, striped bass, cod, tuna) or finding alternatives to more traditionally consumed species (e.g., tilapia in the Americas). The following are some examples to illustrate how development took place with respect to a few species or species groups.

2.5.1 Channel catfish

The prediction that channel catfish (*Ictalurus punctatus*), which had been grown for stocking for many years, could be reared to market size and sold for a profit was first put forth in papers by Swingle (1957, 1958). Swingle speculated that a farmer would need to get US$1.10/kg at the farm gate to make a profit. Now, a half-century later, the farm gate value of the fish has not even doubled. The early work with channel catfish, as was true of many other native fish species being cultured in the United States, began at state and federal government hatcheries. Channel catfish were found to be difficult to spawn but success in pond spawning was finally achieved in the early twentieth century (Shira 1917). The species is native to streams where it spawns under logs, in depressions in riverbanks, or in some other convenient hiding place. Once the cavity spawning requirement was recognized and appropriate nests were placed in ponds, spawning became routine and is practiced today much like it was a century ago (Hargreaves & Tucker 2004).

It was in the state of Alabama where Swingle (1957, 1958) conducted his research that the industry was born. The history of catfish farming in that state was chronicled in a fascinating book by Perez (2006). After World War II, some farmers in the southern United States turned to fish culture. They were first interested in buffalo fish (*Ictiobus* sp.) and later turned to polyculture of buffalo fish with catfish. By the early 1960s, buffalo fish culture was on the way out and was being replaced with channel catfish monoculture (Hargreaves & Tucker 2004). Because of a lack of abundant ground water Alabama catfish farmers had to rely for the most part on precipitation runoff to fill their ponds. A seemingly much better situation with respect to water availability was seen in central Arkansas where rice had been the staple crop. Rice paddies could be fairly easily turned into catfish ponds on the flatlands of the region located to the north of the Ozark Mountains. The US Department of Interior set up one of two laboratories dedicated to fish culture research in 1958 when the Fish Farming Experimental Station was established in Stuttgart, Arkansas. The other laboratory was the Southeastern Fish Cultural Laboratory located in Marion, Alabama. The Stuttgart laboratory was moved to the Department of Agriculture in 1996 and became the Harry K. Dupree Stuttgart National Aquaculture

Research Center, named after a scientist who had been the director at both laboratories, first in Marion, and later in Stuttgart.

The first author of this chapter had the opportunity to spend the summer at the Stuttgart laboratory in 1969. It was at that time that the water table was dropping rapidly due to the massive withdrawals required to meet the needs of both the rice and catfish industries. Catfish farming was rapidly being developed in Mississippi, the state that quickly took over domination of the industry. However, Arkansas, Alabama, and Louisiana still produce considerable volumes of catfish with lesser amounts grown in many other American states.

Once popular only in the southern region of the United States, the demand for channel catfish is now nationwide due in part to an excellent marketing campaign that was launched during the rapid growth phase of the industry. Other factors that contributed to the growth of the industry included the formation of processing and feed cooperatives by the farmers that allowed them to share in the profits from those sectors of the industry while the farm gate value of the fish remained low.

One major problem affecting sector growth had been the seasonality of catfish availability. The fish require about eighteen months to grow from hatching to the typical harvest weight of about 0.5 kg. Initially, harvests occurred in the fall and were associated with complete draining of the ponds. In response to the market demand for year-round availability of fresh catfish, the procedure was changed to one in which partial harvesting is practiced at intervals throughout the year. Fingerlings are added to replace the fish that are harvested in a process known as understocking. The ponds are not drained during the harvesting process. Seines of certain mesh sizes selectively harvest the size of fish that the buyer prefers. Those of the preferred size—which can vary depending upon the market to which the fish are to serve—are loaded on trucks for live-hauling to the processing plant and those not needed are released back into the open pond. Ponds are often operated in this manner for several years without being drained.

The 1970s was a period of consolidation as the number of farms was reduced while the area under culture increased greatly as many farmers failed and the successful ones expanded their holdings (Hargreaves & Tucker 2004). Government and university research led to the development of high-quality formulated feeds containing little or no fish meal or other animal protein; it also addressed various disease problems, developed aeration devices that effectively maintain dissolved oxygen in heavily stocked ponds, and addressed a series of other issues that faced the industry. Off-flavor was (and continues to be) a major issue particularly during the warm months. A process has been developed whereby a few fish from a pond scheduled for harvest are taken to the processing plant for taste testing a week or two in advance of harvesting, the day before and when the truckload of fish reaches the processing plant. If the fish have off-flavor (often described as an earthy-muddy flavor), they are rejected. Blooms of certain algae are the source of the chemicals that cause the off-flavor, and given time, the blooms will dissipate and the fish will metabolize the off-flavor producing chemicals.

In 2005 the industry produced 275,757 metric tonnes of channel catfish, down from the high of over 300,000 metric tonnes in 2003. Production has continued to fall with the 2007 production estimated at 224,500 to 229,000 metric tonnes (Anonymous 2008). According to the National Agricultural Statistics Service (NASS 2008), the amount of channel catfish processed through November 2008 was up several percent over 2007. Imported basa (*Pangasius bocourti*) from Vietnam compete with channel catfish in the marketplace and for some time were available at a lower price. A regulation was put in place that prohibits marketing of basa as catfish in the United States. In addition, and more broadly, the United States has adopted country of origin labeling (COOL) on imported fishery products. Those regulatory changes may have contributed to increases in the price of basa relative to that of channel catfish.

Brazil is also now producing channel catfish, some of which are exported from that country to the United States. China is also growing channel catfish and sent over 260,000 kg to the United States in 2007 (NASS 2008). Imports of frozen basa and channel catfish to the United States during the first nine months of 2007 amounted to 28,760 tonnes (Anonymous 2008). Other nations that export catfish of various species to the United States include Cambodia, Indonesia, Malaysia, Spain, and Thailand (NASS 2008). The plight of catfish farmers from foreign competition has been exacerbated by current high feed costs. Still, channel catfish represent the largest component of commercial fish farming in the United States. Rainbow trout run a distant second with 27,504 metric tonnes of production in 2005 (United States Department of Commerce 2007).

2.5.2 Tilapia

Maar *et al.* (1966) indicated that the first attempts to culture tilapia occurred in Kenya in 1924, followed by the Congo in 1937. Pond trials were initiated in Zambia in 1942 followed by Rhodesia in 1950. While native to Africa and a portion of the Middle East (Philippart & Ruwet 1982), tilapia were introduced to parts of Southeast Asia in the 1930s and are thought by today's inhabitants of such nations as the Philippines to be native. The majority of the tilapia produced for human consumption are in the genus *Oreochromis,* with Nile (*O. niloticus*) and blue (*O. aureus*) and red hybrid tilapia (produced from various crosses) being the most popular. Mozambique tilapia (*O. mossambicus*) are still produced in some countries but are no longer the most highly preferred species by culturists. Mozambique tilapia were introduced to the United States in the 1960s (Stickney 1996) followed by various other species, including blue and Nile tilapia. One or more species were later spread into various countries in Latin America and the Caribbean region often by scientists involved in foreign aid projects in the tropics aimed at increasing the human food supply. Rural farmers could easily be taught to rear tilapia and could do so without the need for any sophisticated methods or technology. In addition to being easy to produce, tilapia are usually readily accepted by consumers. Most of the distribution of tilapia around the world was made before issues associated with exotic introductions developed.

Stunting and overpopulation are significant negatives associated with tilapia pond culture. Hand sexing is possible once the fish reach the appropriate size but is time consuming and subject to human error. One means of dealing with the problem was found the 1960s when monosex populations of tilapia were produced in Israel through hybridization (Sarig 1989). Following that breakthrough, Israeli fish culturists began using tilapia in polyculture with carp and mullet. The creation of all-male tilapia populations by feeding small amounts of male sex hormone to fry tilapia was developed in the 1970s (Guerrero 1975).

Over a period of several years a genetically improved farmed tilapia (GIFT) strain was developed through selective breeding. The effort, largely conducted in the Philippines, has produced fish of exceptional quality and rapid growth that have been widely distributed across the world including back to Africa, the natal home of tilapia. While there is some production of tilapia in the United States—7,803 metric tonnes in 2005 (United States Department of Commerce 2007)—that production cannot begin to meet the demand that has developed in the nation in recent years and continues to grow. Most of the United States experiences winter temperatures that are lethal to tilapia, which limits locales where the fish can be produced year-round to the southernmost regions and Hawaii, with the exception of places that have access to warm water (geothermal or from an industrial source such as power plant cooling water). Considerable numbers of tilapia are being produced in Idaho using geothermal water in a state where the air temperature is well below freezing during extended periods in the winter (fig. 2.3). There is also seasonal production of tilapia in ponds in certain areas of the United States as well as indoor production in recirculating systems. Much of the tilapia imported to North America comes from the Caribbean and

Figure 2.3 Tilapia tank culture facility near Boise, Idaho, uses geothermal water to maintain the proper temperature in a high-temperate climate. (Photo by Robert R. Stickney)