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Tilapia Production Systems in the Americas: Technological Advances, Trends, and Challenges

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ABSTRACT: Tilapia is the common name applied to three genera of fish in the family Cichlidae: *Oreochromis*, *Sarotherodon*, and *Tilapia*. The species that are most important for aquaculture are in the genus *Oreochromis*, including the Nile tilapia, *O. niloticus*, the Mozambique tilapia, *O. mossambicus*, the blue tilapia, *O. aureus*, and *O. urolepis hornorum*. Fish farmers are now growing many strains of these parent species along with many hybrid strains. Native to Africa and the Middle East, these species have become the second most common farm raised food fish in the world.

In the 1960s and 1970s tilapia culture was aimed at the production of food for local consumption, utilizing primarily extensive or semiintensive culture methods with minimal inputs of fertilizer or feeds. However, tilapia culture has expanded rapidly during the last decade as a result of technological advances associated with the intensification of culture practices. These include the development of new strains and hybrids, monosex male culture, formulated diets, a variety of semiintensive and intensive culture systems (e.g., ponds, cages, tanks, and raceways) and the utilization of greenhouses, geothermal, or industrial waste heat and advanced water treatment methods. Marketing programs have also nurtured a growing demand for tilapia in domestic and international markets. Annual worldwide production of cultured tilapia was less than 200,000 metric tons (mt) in 1984 and increased to 1,100,000 mt in 1999.

In the Americas, the increased production of farmed tilapia is due in large part to their adaptability to a diverse array of production systems. These include subsistence level, extensive pond culture in the Eastern Caribbean, integrated animal-fish culture in Guatemala and Panama, semiintensive pond culture in Honduras, intensive pond culture in Colombia, Costa-Rica and Jamaica, semiintensive cage culture in several countries, intensive flowthrough tank and raceway culture in the U.S., and a variety of highly intensive indoor recirculating tank culture in the U.S. In addition, there is increasing production of tilapia in shrimp ponds in Ecuador to ameliorate shrimp disease problems. In this article, representatives of various systems are compared with respect to technological approaches and constraints.

Poor management of tilapia genetic resources is causing a loss of productivity, and research in genetics and selective breeding will be needed to improve production efficiency, fillet yields, and environmental tolerance. Continuing nutritional studies will also be needed to increase efficiency and profitability. With intensification, infectious diseases have become more serious, and fish health management through biosecurity procedures, environmental

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manipulation, reduction of stress, nutrition, genetics, and the use of prophylactic therapeutics will be essential. Increasing waste production will require novel methods for integrating tilapia culture with the production of other valuable crops to maximize nutrient recovery and minimize pollution. Market development and quality control will be critical to ensure market growth.

KEY WORDS: reservoir ranching, ponds, cages, raceways, tanks, recirculating systems.

I. INTRODUCTION

Tilapia is the common name now applied to three genera and species of fish in the family Cichlidae: *Oreochromis*, *Sarotherodon*, and *Tilapia*. Native to Africa and the Middle East, these species have been distributed throughout the world and have become the second most important food fishes in the world (Fitzsimmons, 2000b). In the Americas, the species that are most important to aquaculture are in the genus *Oreochromis*, including the Nile tilapia, *O. niloticus*, the Mozambique tilapia, *O. mossambicus*, the blue tilapia, *O. aureus*, and *O. urolepis hornorum*. These species will readily hybridize in captivity, and many strains of these parent species along with many hybrid strains are now available to growers.

A. CULTURE ATTRIBUTES

Tilapias possess an impressive range of attributes that make them ideal for aquaculture. They have good-tasting flesh with a mild flavor, are widely accepted as food fish, are used in many cuisines, and their consumption is not restricted by religious observances. Several color variants meet the preferences of different consumers. From the standpoint of reproduction, they breed freely in captivity without the need for hormonal induction of spawning. Tilapias used in aquaculture are mouthbrooders and provide a high level of parental care; eggs are large, producing large fry at hatching that are hardy and omnivorous at first feeding. All of these factors result in a simple hatchery technology. They reach sexual maturity in less than 6 months, which is advantageous for selective breeding. They are tolerant of a wide range of environmental conditions (Chervinski, 1982), including low dissolved oxygen levels (1 ppm); high ammonia levels (2.4 to 3.4 mg/L unionized), and will grow in water ranging from acidic (pH 5) to alkaline (pH 11). Various strains can be grown in water varying in salinity from fresh water to full strength seawater (Watanabe *et al.*, 1997).

A fundamental advantage of tilapia for aquaculture is that they feed on a low trophic level. Members of the genus *Oreochromis* are all omnivores, feeding on algae, aquatic plants, small invertebrates, detritus and associated bacterial films, as well as a variety of feeds of animal origin. This makes them relatively inexpensive to feed and suitable for rearing under extensive or semiintensive conditions that depend on the natural productivity of a water body, with minimal inputs of feed or fertilizer, or under intensive conditions that can be operated with lower cost feeds. As omnivores, tilapia are able to grow rapidly on lower protein levels and tolerate higher carbohydrate than many carnivorous species cultured. In intensive systems, tilapias have the advantage that they can be fed a prepared feed that includes a high percentage of plant proteins. These inputs are considerably less expensive than the high-cost feed containing a high percentage of fish meal or other animal proteins that must be fed to carnivorous fish that feed on higher trophic levels. They can be grown under high densities and are relatively disease resistant under these conditions, an important attribute relating to yield potential.

B. HISTORY OF TILAPIA AQUACULTURE IN THE AMERICAS

Introduction of tilapias to the Americas began around 1949, when the Mozambique tilapia *O. mossambicus* was introduced from Malaysia into the southern windward Caribbean Island of St. Lucia. These introductions were promoted by C. F. Hickling, who was Fisheries Officer for Her Majesty's Colonial Office in London (Courtenay, 1997; Ramnarine, 2000). Supported by the Food and Agriculture Organization (FAO) of the United Nations, *O. mossambicus* were then introduced from St. Lucia to many other Caribbean Islands from 1950 to 1953 and to Guyana in 1964, their first introduction to South America (Atz, 1957; in Courtenay 1997). Early introductions of Mozambique tilapia in the Caribbean and Central and South America were made largely to reduce mosquitoes through aquatic vegetation control, as ornamental fish, and to provide fish for public consumption (Courtenay, 1997). In the U.S., the first shipment of Mozambique tilapia for aquaculture experimentation was from the Steinhart Aquarium, California Academy of Sciences, to Auburn University in 1954 (Swingle, 1960).

Much effort was spent during the 1960s and 1970s at developing the tilapia culture industry with *O. mossambicus* in many countries of central and south America as a means for improving the nutrition of the rural poor (Lovshin and Pretto, 1983; Popma and Rodriguez, 2000). However, Mozambique tilapia was poorly accepted and commercial culture never materialized for a number of reasons. The inbred *O. mossambicus* developed a muddy taste, which discouraged consumers. The dark color of these fish also discouraged customers. Farmers practiced subsistence culture, with little attempt at controlled fingerling production, water quality management, pest control, and feeding. Uncontrolled reproduction and mixed sex culture resulted in numerous stunted and unmarketable fish. Without an extension education program, farmers had little opportunity to learn about economically viable culture techniques and population control methods for tilapia. Furthermore, in some countries (e.g., Colombia) concerns arose about possible negative impacts of Mozambique tilapia on native fish fauna and on the freshwater capture fishery. This resulted in resistance by prospective producers and an eventual prohibition of its culture and transport (Popma and Rodriguez, 2000). Currently, no large-scale culture of *O. mossambicus* occurs in the Americas.

An important technological advance in the development of the tilapia industry in the Americas beginning in the 1960s was the introduction of three other species of tilapias, which gave researchers and culturists the opportunity to undertake selective breeding and hybridization to develop superior species, strains, and hybrids for culture. In 1957, a group of 10 *O. aureus* was introduced from Israel to Auburn University (Swingle, 1960). All of the *O. aureus* in the southeastern U.S. are likely derived from this founder population and are probably severely inbred (Hargreaves, 2000). Nile tilapia originating from the Ivory Coast was introduced to

Brazil in 1971 and then to Auburn University in 1974. Other introductions of Nile tilapia to the U.S. occurred from Israel and from the Nile river delta of northern Egypt in 1982. Nile tilapia was introduced into Colombia in 1979. *O. urolepis hornorum* were introduced to Auburn University from the Ivory Coast via Brazil in 1974 (Smitherman, 1988).

Red tilapias are examples of the development of commercial hybrid strains. While the genetic heritages of red tilapias are not well documented, their derivation is generally attributed to crossbreeding of mutant reddish-orange *O. mossambicus* (a normally black species) with other species, including *O. aureus*, *O. niloticus,* and *O. urolepis hornorum* (Fitzgerald, 1979; Behrends *et al.*, 1982; Galman and Avtalion, 1983; Kuo, 1984). In the U.S., red tilapia hybrids were first developed in the late 1970s by a commercial fish breeder (Mike Sipe) in Florida. Inbreeding of a population of *O. mossambicus* produced a mutant with reddish-yellow pigmentation that was selectively bred to enhance the red and yellow coloration, resulting in a marked decline in growth and body conformation. In order to restore these qualities, mutant male *O. mossambicus* was crossbred with female *O. urolepis hornorum* (a black-colored species) to produce a first generation (F1) red hybrid. In 1981, other commercial culturists began a selective breeding program with the F1 hybrids and by the end of 1983 developed a relatively true breeding strain of red tilapia. Fish descended from F1 progeny became known to aquaculturists as the "Florida red" strain. The Florida red strain was introduced to the southeastern U.S., the Caribbean, Central and South America, as well as Southeast Asia and the Middle East. Researchers and commercial growers in the U.S. and Jamaica have crossbred the Florida red strain with other species, including *O. aureus,* to improve cold tolerance (Behrends and Smitherman, 1984) and *O. niloticus* to improve growth rates (R. DeWandel, pers. comm.). Florida red tilapia, as well as their three- and four-way hybrid crosses with *O. aureus* and *O. niloticus,* were introduced into various parts of the Caribbean and Central and South America (Popma and Rodriguez, 2000; Green and Engle, 2000).

Other strains of red tilapia with distinct genetic heritages have also been introduced into the Americas, including Taiwanese red tilapia (*O. mossambicus* × *O. niloticus*) (Galman and Avtalion, 1983; Liao and Chang, 1983), a red strain from Israel developed from a pinkish *O. niloticus* from Egypt crossed with normal *O. aureus* (Hulata, Karplus, and Harpaz, 1995), and a red line of tilapia (heritage not described) developed in Stirling, Scotland (Popma and Rodriguez, 2000). Due to uncontrolled transfers and interbreeding, the red tilapias used currently in commercial production in the Americas are of uncertain genetic lineages and have likely resulted from interbreeding of these various strains. Recently, another line of red tilapia from Israel (designated as ND-59) was imported by a private company in Honduras (Popma and Rodriguez, 2000).

Red coloration is critical in many areas of the Caribbean and central and South America due to a consumer preference for red-skinned fish and a cultural bias against freshwater fish and against fish with the silver-black appearance of most common varieties of tilapias (primarily *O. mossambicus*). This has limited the market demand and commercial production of blue and black tilapias in some areas of the Caribbean (Sandifer, 1991; Chakalall and Noriega-Curtis, 1992) and South America (Popma and Rodriguez, 2000). In these areas, red color is critical because fish are typically sold skin-on. The gray color of Nile tilapia is less appealing and cannot be distinguished from wild-caught tilapia that are often tainted by off-flavor. In southern

Colombia, the market value of gutted Nile tilapia in 1997 was 25% of the value of red tilapia (Popma and Rodriguez, 2000). Although red tilapia were originally marketed as "red mojarra" to avoid association with wild-caught tilapia (which has a bad reputation), farm-raised red tilapia rapidly gained market acceptance and the name "tilapia" is now popular in every market (Popma and Rodriguez, 2000).

In some North American markets, light-colored fish have good market acceptance. Some commercial growers in the U.S. use a hybrid strain called Rocky Mountain White tilapia, possibly an interspecific cross between *O. niloticus*, *O. aureus,* and *O. mossambicus* (Hallerman, 2000). The development of these commercial hybrid strains in the Americas was an important reason for the large-scale production that developed in the 1980s and 1990s for domestic consumption and international trade. In the future, an increase in the number of *O. niloticus* and red hybrid strains should become available (Fitzsimmons, 2000b). *O. niloticus* is expected to account for the majority of production, followed by red strains, while *O. aureus* and *O. mossambicus* will be used to create hybrids.

Early maturation and frequent spawning were biological characteristics that caused stunting and overpopulation of fishponds with unmarketable fish. Male tilapia is the preferred sex for culture because of faster growth. Early culturists practiced monosex male culture by manual sexing, a time-consuming, laborious, and wasteful process. A second major technological advance was the finding that recently hatched tilapia fry have undeveloped gonads and that when fish are treated from the beginning to the end of gonad differentiation (a period of about 2 to 3 weeks) with the proper dose of androgen (e.g., methyltestosterone), the resultant fish population will be highly skewed to males (Guerrero, 1975; 1979; Shelton, Hopkins, and Jensen, 1978; Phelps and Popma, 2000). This controls unwanted reproduction and overcrowding during growout and permits faster and more uniform growth. This technique also permitted less acreage to be devoted to broodstock and fingerling production and more to the production of food fish (Phelps and Popma, 2000). Because it is simple and efficient, sex reversal has become the commercial procedure of choice to mass produce male tilapia fingerings and has been a major factor in the rapid growth of the tilapia industry. Methyltestosterone has not yet been approved by the US Food and Drug Administration (FDA) for use in food fish. However, producers are permitted to use this product for sex reversal by participating in an FDA investigation (INAD) aimed at acquiring data needed for approval. While highly effective in intensive systems, hormone sex reversal seems to be less effective in extensive systems. This may be related to lack of skilled technicians and facilities to implement and also to longer growout periods that allow even a small number of females to cause overpopulation (Nogueira da Silva, de Queiroz de Farias, and Pereira, 1997).

Recently, a technology has been developed and commercialized that combines the techniques of hormone sex reversal and progeny testing to produce males that have a novel YY genotype (Scott *et al.*, 1989; Mair *et al.*, 1997). These YY "supermales" yield all male progeny, termed genetically male tilapia (GMT), when crossed with normal XX females. Because hormone treatments used in the process of producing YY males are two generations removed from fish that are consumed, this technology is considered environmentally friendly, requiring no special facilities for application. YY supermales are as viable and fertile as normal males and are now being sold commercially to mass produce GMT for tilapias growers in the Philippines, Thailand, and the U.S.

Finally, a third factor in the growth of the tilapia industry has been the improvement in knowledge of the nutritional requirements of tilapia, particularly for protein, and the availability and quality of commercially available feeds.

II. GLOBAL TILAPIA PRODUCTION

Production of tilapia is widely distributed around the world. The FAO reports production in 85 countries in East Asia, Indonesia, Latin America, Caribbean, the Middle East and Africa, Germany, Belgium, Spain, Canada, Korea, Japan, and most states of the U.S. (Fitzsimmons, 2000b). Total world landings from capture and culture increased from 515,000 mt in 1984 to 1.6 million mt in 1999. Most of the increase in production is the result of aquaculture. Between 1984 and 1995 the contribution of cultured tilapia to total tilapia landings increased from 38% (198,000 mt) to 69% (1,100,000 mt) (Fitzsimmons, 2000b; Josupeit, 2002).

Four species or species groups (*O. niloticus*, *O. mossambicus*, *O. aureus,* and unidentified tilapia) dominate world production. Global production was influenced by rapid expansion of *O. niloticus* culture in China, the Philippines, Thailand, Indonesia, and Egypt. *O. niloticus* dominates global culture, its share of total production increasing from 33% (66,000 mt) in 1984 to 80% (880,000 mt) in 1999 (Fitzsimmons, 2000b; Josupeit, 2002). China is now the leading producer having increased production from 18,000 mt in 1984 to 550,000 mt in 1999 (FAO, 1997; Josupeit, 2002).

A. NORTH, CENTRAL, AND SOUTH AMERICA

Countries of the Americas are relatively small markets and producers compared with China and other Asian countries. Total tilapia production in the Americas was 204,267 mt in 1998. In 1995, the proportions by volume of cultured species in the Americas were *Oreochromis* spp. (red tilapias and other hybrids) 43%, *O. niloticus*, 37%, and *O. aureus* 20% (FAO, 1997). Tilapia production in the Americas increased 13%/year from 1984 to 1995. Production of red tilapia and *O. niloticus* experienced the highest growth throughout the Americas due to high prices in markets and high demand for large fillets.

B. TOP PRODUCERS IN THE AMERICAS

Fitzsimmons (2000b) has provided detailed country descriptions of tilapia production in the Americas. The top ten producing countries are briefly summarized here.

Mexico produced 94,279 mt in 1996 (79,154 mt farmed), more tilapia than any other country in the Americas. The production methods range from stocking of fingerlings released into reservoirs in ranching operations to intensive methods in ponds, lake cages, tanks, and shrimp ponds. *O. aureus* is common in the south of the country and in reservoir fisheries, while *O. niloticus* and red tilapia are widely cultured in intensive operations in northern states. Fish are usually sold fresh whole on ice. There are highly developed internal markets in Mexico and most fish are consumed domestically. With greater intensification and replacement of stocking and recapture with cage culture, production and exports to the U.S. are expected to increase.

In Cuba, 35,000 mt of tilapia are produced annually, mainly from reservoir fisheries. *O. niloticus*, *O. aureus,* and *O. mossambicus* were introduced to several reservoirs around the country in the late 1960s and are now found from headwaters to coastal lagoons. *O. aureus* is the primary species captured in reservoir fisheries, produced in hatcheries, and grown out in ponds and cages. Cuba is an ideal production location, with input low costs, proper climate, and proximity to the U.S. markets. In the future, reservoir fisheries are likely to be replaced by intensive cage culture operations. With ample water resources, it is believed that freshwater production of tilapia in Cuba can be doubled or tripled (Fonticiella and Sonesten, 2000).

Brazil has one of the fastest growing tilapia industries in the Americas, with annual production of 30,000 mt in 1997. An average of 5000 mt of Nile tilapia are captured from public reservoirs in northeast Brazil, while approximately 25,000 mt are farmed in a variety of systems, including semiintensive culture ponds fertilized with animal manures to intensive culture in flowing raceways, tanks, and in floating cages. Most of the farmed tilapia are sold live to fee-fishing operations in the populous southern and southeastern states, but food fish markets are growing rapidly. Red tilapia have been popular with the fee-fishing industry in the southeastern states and are expanding into the food fish markets. Nile tilapia is popular among growers and additional markets for these fish are developing. Many tilapia are sold whole, on ice in neighborhood open markets. Large processing plants to manually clean and freeze tilapia are in operation in some states, and numerous small facilities produce fillets for local sale. A unique feature of the Brazilian industry is the market in tilapia leather — clothing and apparel (belts, purses, wallets, briefcases) made from skins are popular (Fitzsimmons, 2000b). While all tilapia production in Brazil is consumed domestically, Brazil has the potential to become a major supplier to the U.S. and other countries in the future because of its favorable year round climate and abundant low-cost land and water resources. Cage culture on large hydroelectric reservoirs will probably expand if environmental pollution from fish farms can be controlled.

In Colombia, large-scale commercial production of red tilapia developed rapidly between 1994 (8000 mt) and 1998 (18,000 mt) when several farms were built using intensive pond production techniques with rapid water exchange using gravity flowthrough of diverted surface waters (Sepulveda Cardenas, 2000). In the early 1990s, most tilapia was exported as frozen fillets to the U.S.; however, in the mid-1990s, a domestic market for fresh product (whole and fillet) developed and export levels declined. All production is now consumed domestically, and Colombia imports tilapia from Venezuela and Ecuador to meet domestic demand.

The U.S. is a significant producer of farmed tilapia (8200 mt in 1999) and is a major market and center of research and development. Production is mainly in indoor intensive recirculating culture systems that use greenhouses or more heavily insulated buildings to maintain optimum growing conditions in Northern and Midwestern states. Industrial waste heat is used on a few farms. Pond culture is also practiced in Hawaii, Arizona, California, and the southeastern U.S. A number of farms use geothermal water sources to raise tilapia in Idaho, Arizona, California, New Mexico, and Mississippi. Approximately 85% of the tilapia grown in the U.S. is sold live, and 15% is processed into whole fish, headed and gutted whole fish, and fresh fillets (Fernandes, 2000).

Costa Rica is the largest producer (6072 mt in 1998) of tilapia in Central America. Intensive culture of *O. niloticus*, *O. aureus,* and red strains in flowthrough ponds is used. Exports of fresh fillets to the U.S. and a domestic market for tilapia are growing.

In 1977, the government of Jamaica and the U.S.A.I.D. began an Inland Fisheries Development Project to provide nutrition and employment for the rural population and to conserve foreign exchange through import substitution. This project, which ended in 1984, successfully established fish farming as an enterprise in Jamaica, where tilapias comprise 95% of inland fish production (Hanley, 1991). *O. niloticus* production was at 16 mt in 1979, increasing to 126 mt in 1982. However, it was not until red hybrid tilapia were introduced from Florida in 1983 that consumers began to consider farm-raised tilapia as an acceptable alternative to marine fish, resulting in major expansion of production. In 1989, 3000 mt valued at U.S. $8.4 million were produced by 160 farms from 625 ha of ponds. By 1997, 55 farmers operating 300 ha of ponds produced around 4200 mt (Hanley, 2000). Jamaica is another supplier of fresh fillets and whole fish to the U.S., although local demand is strong in rural areas (Hanley, 2000). Farm-raised tilapia larger than 200 g are well received by local consumers, and much of the production is sold pond side by farmers or fresh on ice through small roadside vendors. Large producers sell to supermarkets where the product may be packaged and seasoned, or sold to brokers. Since 1997, fish have been exported to the U.S., Canada, and Europe. An automated processing plant produces frozen whole fish and fillets for local markets and exports. Exports are 20% of total production.

In Honduras, red hybrids were introduced in the 1980s and commercial production for export began in 1989 based on the Jamaican production system. By 1997, exports to the U.S. from these farms (mostly fresh fillets) were 212 mt. In 1997, Aqua Corporacion de Honduras began production using intensive pond system technology developed in Israel. Total production of red strains and *O. niloticus* in Honduras in 1998 was 3000 mt. In 1999, two large cage farms in reservoirs began operation.

In Ecuador, the production of tilapia (2318 mt in 1997) is based on the use of marine shrimp pond facilities. When Taura syndrome struck in the early 1990s, many producers turned to tilapia as an alternative crop, because infrastructure for growout, processing, and marketing shrimp was readily adaptable to grow, process, and transport tilapia to the U.S. Some growers believe that crop rotation of shrimp and tilapia reduces shrimp diseases. Further devastation of the shrimp industry from white spot disease around 1995 caused many more shrimp farms to switch to tilapia or to rotate between tilapia and shrimp.

In Venezuela, 1936 mt of red tilapia and *O. niloticus* were produced in 1997, 95% in semiintensive concrete tank culture (Fitzsimmons, 2000b). Many fish farms are integrated with small farms or ranching operations and some farms grow tilapia in polyculture with “cachama” (*Colossoma macropomum*). Most of the production is consumed domestically and is sold in the round or gutted on ice. A small amount (~ 236 mt) of processed product is exported to Colombia, France, and the U.S. Most new production will be directed to U.S. fillet markets.

In addition to these major producing countries, other countries in the Americas that produce significant quantities of tilapia include Nicaragua (352 mt), Guatemala (260 mt), Belize (147 mt), Suriname (100 mt), Canada (100 mt), Panama (65 mt), Paraguay (60 mt), Trinidad (28 mt), El Salvador (20 mt), Argentina (10 mt), and other nations (120 mt) (Fitzsimmons, 2000b).

To summarize, most large-scale commercial production from the tropics, where production costs are low, is developed for export to the U.S., Europe, and Asia. In Central America, northern regions of South America, and the Caribbean basin, the commercial production of tilapia has expanded in recent years to target North American markets for fresh and frozen fillets. These operations are typically pond based, but more intensive systems using gravity flowthrough of diverted surface waters are also in development. There is a strong and growing domestic market in many producing countries in south and Central America, such as Colombia, Cuba, Brazil, and Mexico. In Colombia and Mexico, for example, domestic demand has absorbed local production, and exports to the U.S. have declined. Most commercial production in the U.S. and Canada, where intensive fish production costs are higher, is for the live fish ethnic market, which brings the highest prices.

Based on current trends, the total production of tilapia in the Americas is expected to double in the next 10 years to 500,000 mt by 2010 (Fitzsimmons, 2000b). Due to cost advantages, most growth will occur in tropical countries, while North America will see a moderate increase that will mainly supply niche markets for live fish and local fresh product. Mexico and Brazil will be major producers and consumers, followed by the U.S. (Fitzsimmons, 2000b).

C. U.S. TILAPIA SUPPLY

The U.S. is a large and expanding market that has stimulated the development of tilapia farms throughout the Americas. Tilapia consumption has grown dramatically in the U.S. over the last decade. In 1992, total tilapia supply in the U.S. was 8000 mt live weight equivalent (LWE), which grew to 52,000 mt LWE by 1998. In 2000 U.S. consumption exceeded 81,000 mt LWE (Fitzsimmons, 2000b). Imports have taken a growing share of the market, representing 40,469 mt (72,428 mt LWE) in 2000, or 80% of the total supply. Tilapia is the third largest imported aquaculture product in U.S. behind shrimp and Atlantic salmon (Fitzsimmons, 2000b). U.S. domestic production grew at a much slower rate from more than 2000 mt LWE in 1991 to over 9000 mt LWE in 1998 (50% per year). Oriental and other ethnic markets are still the primary market for U.S.-grown fish.

It is noteworthy that U.S. consumption of tilapia continues to expand at 20% per year, while there is little or no increase in overall per capita seafood consumption. This is attributed in large part to marketing and the availability of more varied products, including live, fresh, and frozen whole and fillets that cater to both household and institutional consumers (Posadas, 2000). Competitively priced tilapia products are being imported from a variety of countries and new markets are developing as processors develop value-added products (marinated, breaded, and microwave ready) that are gaining market share. The Tilapia Marketing Institute (TMI) was founded in 1998 by several larger producers and marketers to increase awareness and demand for tilapia products. The American Tilapia Association

(ATA), an organization consisting of producers and individuals from government and academia, should also help stimulate demand.

Imports of tilapia to the U.S. are comprised mainly of whole frozen fish, most of which comes from the orient, followed by frozen and fresh fillets, most of which originates in Central America and the Caribbean. In 2000, the value of imported fillets was $68 million compared with $33.7 million for whole frozen tilapia.

The tilapia markets in the U.S. are segmented between live, whole frozen, frozen fillets and fresh fillets. There is a wide price structure and prices vary considerably across the U.S. (Fitzsimmons, 2000d). At the high end is the ethnic market for live and fresh fish that bring $2.20 to 6.60/kg farmgate. Domestic producers supply this market. Fresh fillets are mostly imported from the South and Central America, while frozen fillets come mostly from China, Taiwan, and Indonesia, selling for $4.80 to 7.00/kg wholesale. While prices vary wildly with quality (Engle, 1997a), fresh fillets are sold for around 26 to 66% higher than the frozen fillet price (Engle, 1997b; Josupeit, 2002). Imported fillets are sold to wholesalers and distributors, then to retail grocers and restaurants. Fresh fillets are a rapidly growing market, because this form is sold in grocery stores and used in restaurants. At the low end of the price range is whole frozen fish, imported from Taiwan and China, which sells for $1.10 to 2.00/kg farmgate. Product quality of whole frozen fish from the orient is uneven and prices continue to decline. Fresh fillets have shown the most rapid growth of all product forms. Fresh fillets originate mainly from Ecuador, Costa Rica, Honduras, and Jamaica, and a few U.S. producers who have been distributing fresh fillets.

III. GROWOUT SYSTEMS

In the Americas, tilapias are cultured under a diversity of production systems from extensive to superintensive, small to large scales, mono- or polyculture, fertilization and/or manuring, and/or feeding. The various systems used for commercial production in the Americas are described, with an emphasis on systems for which definitive published data is available.

A. EXTENSIVE CULTURE

1. POND CULTURE

The earliest form of tilapia culture in many areas of the Caribbean and Central and South America was small earthen ponds with no inputs, relying only on natural plankton and detritus present in water and soil (Teichert-Coddington and Green, 1997; Ramnarine, 2000). Extensive pond culture is still practiced in some areas of the Americas such as Mexico, the Dominican Republic, and Jamaica. Families typically consume most of the product and sell a small portion. Using mixed sex culture and low stocking density (1000 to 2000 fish/ha), yields range from 300 to 700 kg/ha/crop. In most developing countries, this type of producer has a low social, cultural, and economic status and limited access to technology, markets, and credit (Alceste, 2000a). While its impact is hard to measure, extensive tilapia culture has helped the rural poor to improve their household nutrition and raise their standard of living in some areas of the Americas (Fitzsimmons, 2000b; Fonticiella and

Sonesten, 2000). In the Dominican Republic, where land and labor are inexpensive, but financial incentives and infrastructure are lacking, only extensive and semiintensive operations will likely prevail during the next decade (Alston *et al.*, 2000).

2. RESERVOIR RANCHING

The most productive form of extensive farming of tilapia in the Americas today is ranching, where tilapia are stocked into public and private reservoirs in a number of Caribbean and the Central and South American countries, including Cuba (Fonticiella and Sonesten, 2000), Mexico (Fitzsimmons, 2000a), and Brazil (Lovshin, 2000). Built to provide electrical power, irrigation and potable water, and flood control, these reservoirs have become valuable as inland fisheries resources. Tilapias harvested from reservoirs are included in the aquaculture statistics because there are stocking programs adding juvenile tilapia.

In Cuba, tilapia culture consists mainly of fingerling production (primarily *O. aureus*) in hatcheries for stocking and extensive culture in reservoirs, where the fish production level relies on the primary productivity in the water body (Fonticiella and Sonesten, 2000). Semiintensive culture is also practiced in small reservoirs, where composted crop residues and manure are added to increase productivity. Mean annual yield of tilapia from Cuban reservoirs during 1977 to 1996 was 186 kg/ha/y. Mean annual yield in semiintensive culture using organic fertilization practices is about 1360 kg/ha/y. A network of hatcheries now covers all provinces of the country.

B. SEMIINTENSIVE CULTURE (PONDS)

As market demands increase, industry expands, and technology development continues, traditional extensive culture methods are being replaced by semiintensive and intensive production systems. In countries with adequate water and land resources, including the Caribbean Islands of Suriname and Trinidad and Tobago (Ramnarine, 2000), Jamaica (Hanley, 1991, 2000), and the South American countries of Brazil (Lovshin, 2000) and Honduras (Teichert-Coddington and Green, 1997), significant production comes from earthen ponds using semiintensive techniques, with nutrient input limited to manure and supplemental feeds with no aeration or water exchange.

Semiintensive pond culture of tilapia is typically integrated with agricultural or animal husbandry activities because pond fertilization with organic (e.g., crop residues or manures) fertilizers can promote natural pond productivity in addition to being directly consumed by the tilapia. In Brazil, for example, 0.1-ha ponds stocked with sex-reversed male tilapia in monoculture or in polyculture with common carp and Chinese carp yield 3 to 4000 kg/ha/crop when ponds are integrated with pig husbandry (Lovshin, 2000). In the U.S., however, semiintensive culture using manures is not practiced due to public perception, even though the costs of using commercially prepared diets are much higher per unit of fish production.

The most detailed description of semiintensive culture in the Americas comes from Honduras (Teichert-Coddington and Green, 1997). In 1983, a project funded by the U.S. Agency for International Development (U.S.A.I.D.) was initiated in

Central America, focusing on increasing natural productivity and fish yields of static water ponds through nutrient inputs without mechanical aeration. A number of semiintensive pond management strategies were tested in Panama and Honduras for Nile tilapia stocked in 0.1-ha earthen freshwater ponds at densities of 10,000 to 30,000 fish/ha (1 to 3/m^2). Nutrient inputs ranged from inorganic phosphorus to various levels of organic fertilizer, combinations of organic and inorganic fertilizer, and combinations of fertilizers and feeds. The economics of these systems were evaluated in terms of income above variable costs and net returns to land and management from enterprise budgets for 150-d growing cycles. Greatest tilapia yields (5300 kg/ha for 150 d) were obtained with feeds; however, a combination of chicken litter (750 kg/ha/week) and inorganic nitrogen (14.1 kg N/ha/wk as urea) yielding up to 3685 kg/ha was just as profitable. Higher fertilizer application rates resulted in low dissolved oxygen, which stressed or killed fish. These authors concluded that semiintensive culture of tilapia without feed may be quite profitable for subsistence level farmers who do not have buildings or equipment (fixed costs), but would not be profitable for large farms producing fish for export (Teichert-Coddington and Green, 1997). Such farms would have to incorporate the cost of pond depreciation and maintenance into their costs. Stocking densities would have to be increased 2 to 5 times, and mechanical aeration and/or water exchange would be needed to maintain water quality. These authors further suggested that growing tilapia with fertilizers until feed became necessary to sustain good growth could minimize the amount of feed required. Because fish of 150 g and higher are consumed in the rural areas of Honduras, pond management to supply these markets may depend on a combination of organic and chemical fertilizers. If large fish (> 300 g) are needed (e.g., by the export market), feed will be required to continue growout.

In Jamaica, the majority of production is a red tilapia strain known as Jamaican red tilapia, generally believed to be descendants of 4-way mosaic of *O. mossambicus*, *O. urolepis hornorum*, *O. aureus*, and *O. niloticus*. Most farms are situated in the south central plains where clay soils and irrigation systems of the sugar industry provide infrastructure for water supply and drainage. The predominant production unit is the earthen pond, 0.4 ha, excavated to 1.5 m deep. Production uses 98% males produced by testosterone sex reversal. A three-phase system of brood, nursery and growing ponds is used. Fingerlings (20 to 50 g) are moved from nursery ponds to growout ponds. On a typical farm, growout stocking densities are less than 30,000/ha, supplemental diets are used, water exchange is minimal (10%/d), and paddlewheel aeration is used occasionally. Fish are grown for 90 to 150 d to 220 to 350 g, with an average survival of 95% (Hanley, 2000). Some producers grow fish to > 450 g in the same time through longer durations of aeration.

C. INTENSIVE CULTURE

1. CAGES

Culture of tilapia in cages is expanding in some countries of the Americas, including Mexico (Fitzsimmons, 2000a), Brazil (Lovshin, 2000), and Colombia (Popma and Rodriquez, 2000). This approach is useful for producers who use public or communal waters, including reservoirs, lakes, bays, irrigation systems, or village ponds. In the U.S., tilapia are being cultured in cages placed in abandoned phosphate mining pits in Florida and in watershed ponds in Alabama (Popma and Rodriquez, 2000). Cages vary widely in construction, from simple bamboo enclosures to complex steel and plastic designs. Capital investment is low compared with ponds, and by concentrating fish the farmer has better control over feeding and harvesting. This method also reduces fertilization and recovery of eggs by spawning fish to minimize unwanted recruitment. Some disadvantages of cage culture include poaching risk, inability to avoid poor water quality conditions, and dependence on nutritionally complete feeds.

In Mexico, cage culture systems include floating cages, net pens that use staked sides and rest on the bottom, and wooden corrals that enclose portions of a lagoon (Fitzsimmons, 2000a). In Brazil, cage culture is expanding rapidly as more nutritionally complete floating feeds become available and as government agencies issue permits for cage culture on public waters (Lovshin, 2000). Cage volumes and stocking densities range from 4-m^3 units stocked at 200 to 300 fish/m^3 to cages of 100 m^3 or larger stocked at 25 to 50 fish/m^3. Yields range from 150 kg/m^3/crop in 4 m^3 cages to 50 kg/m^3/crop in 100 m^3.

In Colombia, cage culture is practiced in large reservoirs constructed for hydroelectric generation (Popma and Rodriquez, 2000). Cages range from 2.7 to 45 m^3 in volume, with total volume exceeding 13,000 m^3 in 1997. Sex-reversed males produced in land-based hatcheries are stocked into growout cages at 30 g and are raised to 150 to 300 g in 6 to 8 months. Fish are fed extruded feeds with 24 to 34% crude protein. Streptococcal infections have been problematic and survival averages 65%. Annual yields at final densities of 160 to 350 fish/m^3 are 67 to 116 kg/m^3 (Popma and Rodriguez, 2000).

2. PONDS AND RACEWAYS

Intensive ponds of 1 ha or less and raceways or tanks supplied with large amounts of flowing water from rivers or streams are preferred for large-scale commercial production in many countries of the Caribbean and Central and South America. In these countries, companies that grow tilapia using intensive systems target a high-quality product for export markets. Such companies have access to monetary institutions to finance production, add value, and ship to distant markets (Alceste, 2000b). In addition to complete water exchange, supplemental aeration with paddlewheels or air injection is usually applied.

Detailed descriptions of intensive pond culture in the Americas have been published for Honduras (Teichert-Coddington and Green, 1997; Green and Engle, 2000) and for Jamaica (Hanley, 1991, 2000). The Honduran intensive pond culture system is modeled after the system utilized in Jamaica, which is described below in greater detail.

There are three levels of farming (small, medium sized, and large) in Jamaica, that illustrates a progression from semiintensive to intensive and highly intensive culture practices. The lowest level is the small farmer with 1 to 4 ha (75% of farms) that usually owns their land. Fishponds are not the only source of income for these small farmers. Final yield averages 9000 kg/ha/y. The second level is the medium size operator with 5 to 20 ha (19% of farms). Fish are sold pond side, but are also sold to distributors or to a contract farming system. Final yield averages 16,000 kg/ha/y. The third level is the large operator with 21 to 45 ha (6% of farms). Large farms are typically partnerships or subsidiaries of larger firms engaged in other businesses. These farms stock at higher densities, use greater water exchange and aeration, and manage integrated systems for maintaining broodstock, producing fingerlings, processing, and marketing. Input costs are higher and feed efficiencies slightly lower, but larger fish are produced, and much greater yields of 45,000/kg/ha/y are generated. The production cost for a medium farm is $1.62/kg, while that of a large farm is estimated at $1.25 to 1.55/kg (F. Hanley, personal communication). This compares with a selling price of $2.65/kg. Major financial inputs are fingerlings and feed, comprising 73% of costs.

The highest level of intensification of pond culture in Jamaica is illustrated by Aquaculture Jamaica Ltd. (AJL), a 42-ha farm in the Parish of St. Elizabeth that produces 1800 mt of marketable fish/year. Sex-reversed fingerlings produced in nursery ponds are moved to growout ponds at 60 g average weight. Growout is conducted in two phases: Phase 1 growout is conducted in 0.5 to 1.0 ha ponds, where fish are grown from 60 to 220 g in 130 d at a density of 137,000/ha with 80% survival. Water exchange is 30 to 50%/d and aeration 2.5 to 7 hp/ha. Fish are fed 30 to 32% crude protein diets and the feed conversion ratio (FCR) is 1.9. Yield is around 25,000 kg/ha. During phase 2 growout, fish are grown to 580 g to 600+ g in 120 to 130 d. Varying combinations of water flow and aeration levels are used during this phase. High-density ponds (0.06 to 1.0 ha) are stocked at 300,000/ha and lower-density ponds (0.5 ha) stocked at 100,000/ha. Water exchange ranges from 1 to 8 pond volumes/d to as high as 24 pond volumes/d, while paddlewheel aeration of 10 to 24 hp/ha may be applied. The level of water exchange depends on availability, which varies seasonally; ponds with high exchange are not aerated. Survival is 92% and FCR ranges from 1.9 to 2.0. Yields from low-density ponds are 47 to 52 mt/ha, while those from high-density ponds are 86 to 200 mt/ha. Superintensive (80 fish/m^3) ponds with exchange rates of 24 pond volumes/d and no aeration produce the equivalent of 1260 mt/ha/y. AJL's flowthrough system uses 53.6 m^3 of water/kg of fish produced compared to 7.3 m^3/kg for the medium size semiintensive farm (with no water exchange but replacing evaporative losses). In comparison, intensive recirculating production systems in the U.S. use about 0.81 m^3/kg (Rosati *et al.*, 1997).

AJL is an integrated enterprise with its own processing plant and uses the HACCP system of hazard control points through the feeding, harvesting, and processing processes. Approximately 50% of production is sold locally, with the remaining product exported to the U.S.A., Europe, and Canada. An important feature of AJL tilapia farming is the contractual system in which a farmer enters a binding agreement with AJL, who supplies fingerlings, feed, technical advice, harvests and buys fish, and restocks ponds. In turn, the farmer must meet the company's standards for production volumes and management practices. AJL has eight contract farms operating 65 ha providing 800 to 900 mt/y to the contract system.

Because investment capital in Jamaica is scarce and startup costs are high, interest in new farms is mainly in contract farming, which guarantees markets and cash flow. Large producers such as AJL that apply more technology to farming are constrained by a shortage of experienced management and technical personnel. In order for tilapia aquaculture to compete with land based animal production, the industry will need to increase efficiency of production and markets through control of genetic resources, improved feeds and feeding programs, improved processing yields, more diverse product presentation, and value-added production. While there are sufficient land resources to expand traditional pond-based production, a diminishing supply of water for agriculture (Ryther, Creswell, and Alston, 1991; Chakallal and Noriega-Curtis, 1992) is problematic. Diversification into brackish coastal sites may be possible, or into marine cage or net pen culture in protected bays on the south coast.

3. INTEGRATED TILAPIA AND SHRIMP PRODUCTION

White spot and other diseases have affected marine shrimp production in several countries, including Ecuador, Panama, Mexico, and Thailand. Some shrimp farmers have turned to polyculture or crop rotation with tilapia as an alternative production system (Fitzsimmons, 2000d). Polyculture may involve growing tilapia and shrimp in the same pond, with fish allowed to free range or confined to floating pens. Sequential polyculture involves raising shrimp and tilapia in separate ponds. On some farms, "conditioned" water from tilapia ponds is gravity fed to shrimp ponds. In others, shrimp pond effluent is gravity fed to tilapia ponds.

Tilapia-shrimp polyculture may provide advantages in several ways. Cannibalism is one of the primary vectors for the transmission of viral shrimp diseases. Tilapia consume dead or moribund shrimp in polyculture ponds, limiting cannibalism as a mode of transmission. Tilapia also consume small crustaceans, which may be disease vectors. Water from a tilapia culture pond, which tends to be predominated by Gram-positive bacteria, may inhibit the spread of *Vibrio* and other bacterial pathogens in shrimp ponds, which are Gram-negative. Tilapia disturb bottom sediments in foraging and nest building activities, which may improve oxidation of the substrate and interrupt life cycles of shrimp pathogens or release nutrients that could improve algal blooms. While growers in South America and Asia have reported reduced shrimp disease and increases in shrimp production in polyculture systems, controlled studies are needed to better understand the underlying mechanisms and the costs and benefits of penaeid shrimp-tilapia polyculture (Fitzsimmons, 2000d).

D. INTENSIVE TANK CULTURE

Cold-intolerance, poor growth, and disease are major problems in the culture of tilapias in areas where water temperatures fall below 20°C. There have been a number of technological advances that have permitted tilapia culture to expand outside the tropics into the colder climatic zones of North America. These include combined intensive-extensive (CIE) systems, closed-cycle, controlled environment systems, geothermal culture systems, and intensive indoor recirculating aquaculture systems (RAS) using advanced water treatment methods.

1. COMBINED INTENSIVE-EXTENSIVE SYSTEMS

In the southeastern U.S., where climatic conditions permit seasonal (i.e., spring through fall) growout in outdoor ponds, a type of recirculating pond system (also called the combined extensive-intensive system (CIE) or Dekel system in Israel) (Diab *et al*., 1992; Mires and Amit, 1992; Mires and Anjioni, 1997) is being used to grow tilapia on some commercial farms (Hargreaves, 2000). In CIE systems water is recycled between a number of smaller concrete growout ponds and a large earthen pond (reservoir), which serves as a biofilter to maintain water quality. Paddlewheel aerators in the pond supply oxygen and circulate water. In these systems, natural productivity plays a minor role in fish nutrition, but plays a critical role in water quality management. The reservoir pond functions as a purification station in which organic solids settle and decompose and/or are consumed by fish. Nitrogen and phosphorus are either immobilized or transformed by bacteria into compounds that have little or no toxicity to fish (Mires and Anjioni, 1997). A volumetric ratio between growout and reservoir ponds of at least 1:10 is required. Fish are also stocked in the reservoir where they participate in the biofiltration process by feeding on partially digested feces that are flushed from the growout ponds.

Hargreaves (2000) described a commercial recirculating pond system (Pratt Farm) producing tilapia and catfish in Eudora, Arkansas. The farm consists of a three-tiered raceway production system coupled with earthen ponds for water conditioning. Each raceway is 4.88 m wide × 10.98 m long × 1.14 m deep (vol. = 61.1 m^3) and is operated with a hydraulic detention time of 8.1 min (180 exchanges/d). Maximum tilapia density in each raceway ranges from 160 to 185 kg/m^3 and maximum loading ranges from 1.2 to 1.5 kg/L/min. Mixed-sex hybrid tilapia (*O. Aureus* × *O. mossambicus* × *O. niloticus*) is grown, and ponds are also stocked with low densities of channel catfish and bighead carp. The volumetric ratio of growout raceways to treatment ponds is 1:118.

2. CLOSED-CYCLE, CONTROLLED-ENVIRONMENT SYSTEMS (ODAS SYSTEM)

A tilapia farm (Solar Aquafarms) developed in the U.S. in the late 1980s combined the features of pond culture with controlled environment tank culture methods (Serfling, 2000). The farm used greenhouses and aerated circular tanks (29.3 m diameter; vol. = 820 m^3) or raceways (18.3 m × 146. 3 m; vol. = 2083 m^3). The unique feature of this culture system was that it eliminated the need for biofilters, because wastewater was treated and bioconverted into natural foods directly in the fish tanks, a process referred to as “ODAS” (Organic Detrital Algae Soup). Suspended detritus and microorganisms (e.g., bacteria, microalgae, and protozoa) are used to convert dissolved and particulate wastes into microbial protein, which is consumed by tilapia. FCR averaged 1.3:1. ODAS thereby reduces the cost of feed and disposal of solid wastes. The microbial soup was thought to have a probiotic effect to inhibit pathogens and eliminate the need for UV or ozone disinfections, but off-flavor was sometimes problematic in this system. Fish yields averaged 65 to 70 kg/m^3/y (673,000 kg/ha/y) and yields of 500 t/ha/y with less than 0.5% daily water exchange were reported (Schroeder and Serfling, 1989). The rate of water use was 0.028 m^3/kg fish produced. Total production cost for live fish delivered to the processing plant was reported to be $1.21/kg, comparable to many tropical countries using earthen ponds. From 1987 to 1993, Solar Aquafarms marketed fresh tilapia fillets to restaurants and retailers, but high labor costs to process fillets and low fillet yields (31 to 34%), coupled with the high live tilapia prices in California, caused a switch to marketing live and fresh whole tilapia.

3. GEOTHERMAL-BASED CULTURE SYSTEMS

Harnessing of geothermal heat has been an important factor in the increased production of tilapia in the U.S. Geothermal fluids, pumped or flowing naturally from artesian sources, are used directly as a culture medium, or as a heat supply for indirect temperature control through heat exchangers. This enables geothermal-based facilities to grow fish faster and during all seasons of the year (Zachritz and Rafferty, 2000). High volumes of water are generally required for direct heat systems, and most applications are for flowthrough raceways or ponds in areas where the use of geothermal fluids is not restricted. Indirect heating using heat exchangers, on the other hand, allows for the independent control of heating, water quality, and culture water flow rates (Zachritz and Rafferty, 2000).

Geothermal fluid temperatures in the U.S. range from 26 to 74° C. At many sites, geothermal water is available at a temperature close to that required for culture. At other sites, geothermal fluids must first be cooled by evaporative cooling, spray towers, or by mixing with a cooler water source. Many farms around the Salton Sea and Imperial Valley area of Southern California use geothermal fluids (Zachritz and Rafferty, 2000). These farms produce a total of 3700 mt/year, most of which is sold live to markets in California.

Relatively little data are available on geothermal-based tilapia culture systems in the U.S. Hargreaves (2000) described an intensive growout facility (Sea Chick, Inc., Escatawpa, Mississippi), which utilizes 26° C geothermal water for culture. Fish are grown to 220 g in ponds and then stocked in circular raceways for growout to market size. Forty-eight 64-m^3 circular tanks (6.7 m diameter × 1.82 m deep) constructed of concrete are operated in a flow-through mode with a water exchange of about 0.33/h. Water is oxygenated in a side-stream flow through a U-tube. Current harvest density is 50 kg/m^3, while farm production averages 4500 kg/wk (Hargreaves, 2000). Water use is estimated at 345 m^3/kg fish produced.

4. INTENSIVE INDOOR RECIRCULATING SYSTEM

The high-priced ethnic market for live tilapia in the U.S. has led to development of the most intensive systems, indoor recirculating aquaculture systems (RAS). Fish are reared in concrete, fiberglass, or plastic-lined tanks supported by a variety of physical and biological filtration systems to maintain water quality and retain the heat in the water that must be added with electric, petroleum, or coal sources of heat. Because RAS require large investments of capital, technology, and skill, cost of production is high, but market prices for live fish may justify the costs, depending on the scale and local market prices. Approximately 75% of the 9000 mt of tilapia produced in the U.S. in 1998 were grown in recirculating systems.

Indoor RAS address a number of concerns to the aquaculture industry: they generally provide a higher degree of environmental control and are the only means for a fish producer to grow tilapia year-round in temperate regions without using a thermal effluent or high flow geothermal heating. These systems require less water and less land area per kg of fish produced than most of the systems mentioned previously. They can be located in relatively close proximity to markets to reduce transportation costs and stress and mortalities during live transport. RAS have the potential to mitigate much of the environmental impact of fish production systems by reducing the volume of water discharged and focusing a higher strength waste into a point source (Losordo, 1997). Waste solids are concentrated as a sludge that is more easily disposed of by land application, treated in aerobic lagoons, or discharged to municipal waste treatment systems. Finally, RAS can increase biosecurity by minimizing the interaction of cultured fish with external biota to maintain integrity of both natural systems and the cultured stocks. This will be critical toward the use of genetically engineered fish in aquaculture.

5. GREENWATER GREENHOUSE RAS

In the southeastern U.S., where moderate climatic conditions prevail, some RASs are operated in greenhouses. In these "greenwater" systems (Hargreaves, 2000), phytoplankton populations are allowed to develop. Fish are fed nutritionally complete diets, but the periphyton and/or phytoplankton may enhance the nutritional value of applied feeds by supplementation of tilapia diets with vitamins and other nutrients.

Hargreaves (2000) described greenhouse-enclosed greenwater recirculating culture systems being used by a number of commercial operations in the state of Louisiana. These systems are modeled after a tank system designed by Mr. Steve Abernathy (Til-tech Aquafarms, Roberts, Louisiana) to minimize facility costs. In-ground tanks dimensions (4.88 m × 29.28 m × 1.22 m) are designed as multiples of 4 × 8 ft plywood sheets. A 40-ml polyester-reinforced polyethylene liner is installed inside the framework. Perforated PVC pipe functions as water intake manifolds along the tank floor. Water is then pumped through two 0.56 m^3 propeller-washed bead filters, or one 2.83 m^3 paddle-washed bead filter, then returned to each tank through a perforated distribution manifold along the top sides of the tank. Vertical pump aerators placed in each tank provide oxygen (Hargreaves, 2000).

Another unique aspect of the Til-tech Aquafarm system is the use of a series of net pens suspended within the tank, which allows physical isolation of different size or family groups within a system and facilitates concurrent stocking and harvesting. This layout has also been adopted by growers in FL, IL, and MD (Lutz and Roberts, 1998; Abernathy and Lutz, 1998). The serial cohort net pen system maximizes system throughput and production-to-capacity ratio. An economic analysis of a model system producing 45.5 mt/year based on this system indicated a production cost (direct expenses plus depreciation) of $2.62/kg (Lutz and Roberts, 1998).

6. CLEARWATER RAS

In temperate regions of North America, including the Midwest, the Northeast, the mid-Atlantic and Canada, tilapia are grown in recirculating systems situated in well-insulated structures. Such systems are described in relation to greenwater systems, as "clearwater" systems (Hargreaves, 2000) and require a full range of water treatment components. In North Carolina, an indoor RAS system that uses water reuse technology developed and/or tested at North Carolina State University has been thoroughly evaluated and described (Losordo, 1997; Hobbs *et al.*, 1997; Twarowska, Westerman and Losordo, 1997; Losordo, Hobbs and DeLong, 2000). The production system consists of a 5.1 m^3 quarantine tank, a 13.3 m^3 secondary quarantine or nursery tank, and four 60 m^3 growout tanks housed in a 39.6 m long by 9.75-m-wide agricultural barn structure called a "Fish Barn". Water quality in the growout tanks is maintained by a water treatment system consisting of a particle trap and sludge collector, drum screen filter, a trickling biological filter, and a downflow oxygen contact column (Losordo, Hobbs, and DeLong, 2000). Approximately 20% of the total solids that are input to the system as feed are removed by the particle trap and associated sludge collector in a small, 30-l min (lpm), flow-stream (Twarowska, Westerman, and Losordo, 1997), while the drum screen filter removes an additional 30% of these solids. Hence, waste solids are removed quickly and the suspended solids levels in the tank remain very low. TAN level is also maintained low, because the amount of solids undergoing bacterial decomposition is not very large, and the biofilter removes about 50 to 65% TAN on a single pass through the filter.

Tilapia culture is conducted in three phases: during the quarantine/nursery phase, fish are grown from 1 to 2 g to 25 g in 42 days. Fish are then transferred to the second nursery tank where they grow to approximately 100 g in an additional 42 days. During the initial phase of growout, a tank is stocked with 14,000 tilapia (159 fish fish/m^3) where the fish are grown from 100 g to 350 g in an additional 84 days (maximum culture density = 82 kg/m^3). At day 168, the fish in the growout tank are split evenly and transferred to a second growout tank. Both populations grow for another 42 days and reach a harvest size of between 567 and 640 g. Final biomass density is 75 kg/m^3. With four growout tanks, and appropriate movement and splitting of the populations, one harvest can occur every 42 days (6 weeks) to yield an overall yearly production of between 45 to 60 mt (depending on the final average harvest weight of the fish). Water use ranges from 0.11 to 0.21 m^3/kg fish produced.

Based on early performance data generated at the Fish Barn project in North Carolina, an economic analysis of a RAS was conducted (Losordo and Westerman, 1994) that reported an initial investment of $4.34 per kg annual capacity for an intermediate-scale RCS in North Carolina, with an overall production cost of $2.79 per kg ($1.27/lb). Recent study results that reflect improvements in the production system, feed quality, and fish genetics suggest that the production cost of tilapia in the NC Fish Barn are at best $2.47/ kg with a reduced investment cost of $3.55 per kg of annual production capacity. Even with these improvements, production costs are probably too high to compete in wholesale fish fillet market. However, they can be supported by the local markets for live or whole fresh tilapia on ice.

Through sensitivity analyses, Losordo and Westerman (1994) identified production and engineering improvements that could improve economic viability. Changes in either system production yield, either by increasing stocking densities or growth rates, or reduced overall system cost had greater impacts on production cost than changes in any other variable. For example, increasing production rate by 10% caused a 4.1% decrease in production cost due to more production for the same fixed investment. A 10% reduction in overall investment yielded a 3.5% decrease in production cost (at the same production rate). When FCR was reduced from 1.3 to 1.17, overall production costs was lowered by 3.2%. This suggests that production costs can be lowered significantly if a feed that produced a better FCR were available at reduced cost. RAS are assumed to be energy intensive; however, the sensitivity analysis indicated that a 10% change in electric cost caused only 1.5% change in total production cost of fish. Similarly, a 10% change in engineering performance variables (e.g., pump efficiency, biofilter efficiency, aeration efficiency, 0_2 transfer efficiency) caused no more than a 0.5% change in total production cost. This suggests that expending a great deal of research and development in improving performance efficiency of these components may not be justified.

To summarize, the results suggest that future efforts in RAS should be in intensification of systems without making them more expensive. Cost savings can result from reducing overall cost of RAS while maintaining component reliability and longevity. Component performance, on the other hand, is not of primary importance. Where possible, carrying capacity of a system must be increased without increasing cost.

Because of the high costs of growing tilapia in RAS, some growers foresee tilapia as a test species for indoor RAS that will eventually be replaced by higher value species (Engle, 1997a).

IV. FUTURE CHALLENGES AND RESEARCH NEEDS

Due to the large number of systems and microeconomic variables, it is difficult to generalize which types of systems will be profitable in the Americas and which ones will not. Based on current production trends, a variety of systems will likely be effective, from extensive in the tropics to highly intensive in temperate zones, where proximity to markets and maximal growth will offset higher production costs. In some countries such as Cuba, Brazil, and Mexico, there is still ample land and water resources for expansion of extensive culture, and large earthen pond farms with many hectares of fresh water will probably become the predominant method of tilapia production in these areas. In general, however, access to freshwater supplies will become one of the most pressing environmental and economic issues in both the developed and industrialized world (Hankins, 2000). The environmental impacts of aquaculture effluents will also be of growing concern (Goldburg and Triplett, 1997). Even on tropical pond farms, water inflow will be limited to maintenance of water levels and effluents from ponds minimize to conserve water and reduce potential for pollution. In some countries, because of decreasing availability of high-quality freshwater for aquaculture, there will be increasing pressure to use water resources not fit for human consumption or agricultural crops, including brackish water or seawater (Gilles, 1997; Watanabe *et al.*, 1997; Suresh and Kwei Lin, 1992, Stickney, 2000).

Hence, in both tropical and temperate zones future development of tilapia aquaculture in the Americas will depend on the ability of production systems to produce more fish with less water, less food, and less time to lower production costs and reduce pollutants to the environment, a process known as intensification. Complete diets, aeration, water reuse, and disease control will be important factors in this regard. To improve production efficiency, a number of challenges and research issues are of greatest concern to tilapia culturists in the Americas. These include a loss of species/strains, improved growth, fillet yield, environmental tolerance, disease resistance, off-flavors, waste management, and marketing.

A. LOSS OF SPECIES/STRAINS

Because many hatcheries have been established with small founder stocks, unintentional inbreeding, leading to a loss of genetic diversity, has caused declining performance on many farms (Owusu-Frimpong, Behrends, and Hargreaves, 1997). Microsatellite DNA markers have found some strains with heterozygosities of less than 10% of that found in wild stocks (Kocher, 1997). There has also been a loss of pure species due to mismanagement of interspecific hybridization (McAndrew, 1993), a technique used to produce all-male fry. Declining performance of farmed tilapia has also been caused by contamination of improved strains by introgression from feral species (Kocher, 1997). Due to uncontrolled hybridization, some commercial strains (e.g., red tilapias) are of uncertain genetic heritages. There is little or no data on comparative production characteristics of different lines of red tilapia grown in the Americas, no clear consensus among producers on the merits of these lines, or how they should be perpetuated and improved. The certification of pure stocks, careful selective breeding, a systematic program of broodstock exchange among hatcheries, and the use of genetic resources from the wild are needed to maintain and increase genetic diversity (Owusu-Frimpong, Behrends, and Hargreaves, 1997).

B. IMPROVED GROWTH

The most significant methods for improving production efficiency is through faster growth and improved feed utilization, because these reduce time to market, increase system throughput, and reduce waste, all of which will lower the cost of production. The development of genetically improved production stocks can be achieved through selective breeding approaches, such as individual or family selection (Gjedrem, 1999). The GIFT (Genetic Improvement of Farmed Tilapia) strain in Southeast Asia has demonstrated that growth rates of tilapia can be significantly improved through a breeding program involving selection of diverse genetic groups of *O. niloticus* (Beniga and Circa, 1997; Eknath and Acosta, 1999). Chromosome manipulation techniques in tilapia have shown promise for improving growth rates and profitability. In *O. niloticus*, for example, the growth of triploid males and females exceeded diploids by 66% and 95%, respectively (Jeong, Hue, and Kim, 1992; Bramick *et al.*, 1995). Genetically male tilapia (GMT), produced from novel YY males (a technology that involves hormonally induced sex reversal), has shown potential for improved growth and profitability (Roderick, 1997; Mair *et al.*, 1997). The development of highly inbred lines and hybrids with superior growth can also be accelerated through gynogenesis. Finally, biotechnological approaches such as insertion of new genes into the tilapia genome have high potential (Hallerman, 2000). Transgenic tilapia containing an exogenous growth hormone (GH) gene construct have been shown to exhibit dramatic growth improvement (Rahman and Maclean, 1997; Cabezas *et al.*, 1997). At present, it is unclear if such transgenes can be transmitted over many generations and what additional effects they may have on the physiology of the animal.

The genetic improvement programs will need to develop production stocks that are suited for each environment. Farms undertaking selective breeding programs must make significant investments for facilities to maintain broodstock, labor, feed, data handling, estimation of breeding values, and selection of broodstock. Therefore, success in genetic improvement programs will require long-term support and collaboration between partners from industry, university, and government (Hallerman, 2000).

Nutritional research is also critical to improve growth and to further increase efficiency and profitability. New genetic combinations affect nutritional requirements, and availability and pricing of raw ingredients will impact the manufacture of commercial diets. More research is needed on how specific nutritional needs (e.g., optimal digestible protein to digestible energy ratios) vary with species, age, production system, salinity, and temperature (Hanley *et al*., 1997; Maugle and Fagan, 1998). New ingredients, particularly agricultural byproducts, need to be continually evaluated. Research is also needed on diet manipulation to alter physical characteristics of feces to reduce the costs of isolation and removal.

Feed costs and waste levels can be minimized, not only through better feeds, but through better feeding practices. Feeding schedules that include short periods of food deprivation can substantially lower labor and feed costs, without a loss of productivity (Melard, Baras, and Desprez, 1997). Definitive data on growth and feed conversion of tilapia fed by hand or through use of automatic or demand feeders are lacking.

Fishmeal, the major animal protein ingredient in fish diets, is expected to become an increasingly expensive and controversial commodity for use in aquaculture feeds, and substitution with lower-cost plant proteins is needed (Dong *et al*., 1993; Chamberlain 1993; Goldburg and Triplett, 1997). Recent studies have shown that tilapia have the ability to digest and utilize various plant proteins fairly efficiently (El-Sayed, 1999). Seeds of *Salicornia*, a salt marsh plant (Belal and Al-Dosari, 1999), and *Azolla*, an aquatic fern, can replace up to 40% and 30%, respectively, of a fishmeal-based diet for Nile tilapia without affecting growth (Naegel, 1997). Solar-dried duckweed could replace up to 30% of the fishmeal in Nile tilapia diets containing 30% crude protein (Fasakin, Balogun, and Fasuru, 1999). Up to 30% of fishmeal protein in hybrid tilapia (*O. niloticus* × *O. aureus*) diet could be replaced with either defatted or full-fat soybean meal (Shiau *et al*., 1990). In Nile tilapia, anchovy fishmeal could be totally replaced by soy protein concentrate (SPC) in the diet without an adverse affect on growth, feed conversion, and fish body composition (Abdelghany, 1997). SPC is cheaper than fishmeal, contains comparable level of protein to fishmeal, and contains comparable levels of essential amino acids (except for methionine and lysine). In Nile tilapia, the replacement of fish meal with plant proteins and synthetic amino acids (lysine, tryptophan, and threonine) did not affect growth performance (Wu *et al*., 1999). In hybrid tilapia (*O. niloticus* × *O. aureus*), a fish-meal-free diet, with 3% di-calcium phosphate and 2% oil as the only supplements resulted in growth performances and body compositions equal to those on a commercial fish-meal diet (Viola, Arieli, and Zohar, 1988).

C. IMPROVED FILLET YIELDS

While U.S. growers are attempting to enter the fillet market, the high cost of labor to process and package fillets, combined with low fillet yields of tilapia (31 to 34%) have made the fillet market difficult to enter (Fernandes, 2000). If U.S. growers can develop stocks genetically improved for fillet yield and more efficient automated equipment, tilapia grown in the U.S. could become competitive in the fresh fillet market.

D . IMPROVED ENVIRONMENTAL TOLERANCE

Tilapia are known for wide environmental tolerances, but rapid growth occurs under relatively narrow ranges. Improved environmental tolerance in tilapias could permit outdoor culture practices to expand into areas of lower temperature and higher salinities. In RAS, higher nitrate tolerance is advantageous, because nitrate levels often exceed 100 mg/L (and can reach 200 mg/L), and prolonged exposure to elevated levels of nitrate may decrease immune response and induce mortality (Plumb, 1997). The potential for improving environmental tolerance of tilapia by selective breeding or other genetic manipulations has not been fully exploited. Red tilapia hybrids with improved cold tolerance have been developed by introgressive breeding with *O. aureus* (a cold-tolerant species) (Behrends and Smitherman, 1984; Behrends, Kingsley, and Bulls, 1990). The future development of stocks with improved environmental tolerances can be accelerated through the greater use of genetic markers for broodstock management, identification of loci controlling quantitative traits, and the development of superior strains through marker-assisted selection (Kocher, 1997; Agresti *et al.*, 2000). The application of transgenics to such production characteristics will require the identification of genes responsible for these traits.

With new genetic combinations, optimal environmental conditions may change and optimal temperatures, salinity, pH, DO, and acceptable levels of wastes will need to be determined. Finally, it should be noted that in some areas of the U.S. stocks with improved environmental tolerances (e.g., cold tolerance) may not be permitted for aquaculture, even in indoor facilities, because of concerns of escapement and increased possibility of unwanted introductions into nonnative environments.

E. IMPROVED DISEASE RESISTANCE

As culture practices for tilapia have intensified, and densities of fish grown in various systems have increased and culture has expanded into colder climates where proper environmental conditions are more difficult to maintain, infectious diseases, for example, bacteria in the genera *Streptococcus*, *Aeromona*, *Pseudomonas*, *Vibrio,* and *Edwardsiella* have emerged (Plumb, 1997; Stickney, 2000). *Streptococcus* has become the most serious bacterial pathogen of intensively cultured tilapia in the Americas (Crosby, 1996; Baya, 1996). Rearing under elevated salinities increases susceptibility to disease under reduced temperature (Watanabe *et al.*, 1997). Chemotherapeutic treatments are possible, but the U.S. F.D.A. currently approves no drugs or chemicals for use on tilapia. Improved methods for fish health management through environmental manipulation, water quality stability, reduction of stress, and use of prophylactic therapeutics are needed to control diseases (Plumb, 1997).

F. OFF FLAVORS

Off-flavor has occurred in some pond-reared fish and fish produced in RAS (Stickney, 1997). The chemical geosmin has been found in association with off flavor. Research is needed to develop depuration systems and to control blue-green algae or to limit access to benthic algae and fungi.

G. WASTE MANAGEMENT

Limited water resources and increasing public awareness of the need to reduce and control effluents has created a difficult social, regulatory, and economic environment for aquaculture facilities (Summerfelt, 1998). The aquaculture industry is faced with developing profitable production systems, while minimizing environmental impact, and improving public perception (Hankins, 2000). RAS greatly reduce the volume of wastewater discharged from an operation, but particulate matter, for example, feces and uneaten food particles filtered from the culture system, must be discharged in the form of sludge (Summerfelt, 1998). Sludge is rich in nutrients and high in total suspended solids and biochemical oxygen demand and can cause oxygen depletion and nutrient-enrichment problems in receiving waters. Currently, sludge treatment and disposal options include: discharge to municipal wastewater treatment facilities, landfill dumping, composting, infiltration through soil filters, and use as crop fertilizer. Other options that will need more study in future include constructed wetlands, which are cheaper to construct and operate and integrated aquaculture, where wastes are recycled to produce other valuable products such as hydroponic vegetables.

H. LAND APPLICATION

The most common aquacultural sludge management strategy is direct land application when the expense of hauling can be mitigated by spreading on suitable crops in close proximity to the farm (Chen, 1996; Lindell, 1996). This approach is also limited by climatic conditions and local environmental sensitivities; odors are a problem and sludge needs to be injected or the soil immediately tilled after spreading. Alternatively, stabilization of the sludge is desirable to render it biologically inert. Compost made from sludge, fish mortalities or processing waste could provide an effective source of nutrient-rich organic matter with low heavy metal content, soluble salts and bulk (Shelton, Hinshaw and Thompson, 1998).

I. CONSTRUCTED WETLANDS

Natural wetlands play an important role in restoring the quality of water that passes through them by reducing suspended solids, removing nitrogen and phosphorous nutrients, and trapping or converting other natural or man made pollutants (Massingill *et al.*, 1998). Constructed wetlands can replace loss of natural wetlands; provide new plant and animal habitat, aesthetic and recreational environments for people, and water treatment systems for municipal, industrial, and agricultural and aquacultural wastewater. They are more cost-effective than typical wastewater treatment plants, because they involve lower construction and maintenance costs, simpler designs, and lower pumping heads. More study is needed to understand the mechanisms at work within natural wetlands and to model and incorporate water treatment features into artificial wetlands for aquaculture facilities.

J. INTEGRATED AQUACULTURE

In the late 1980s, the J.R. Simplot facility in Idaho was designed to convert organic waste from potato processing into tilapia production. Lagoons were built to treat wastewater produced by this large-scale facility, using water hyacinths to renovate water. An enormous volume of plant material was produced, creating an additional waste disposal problem and cost burden (Ismond, 1996). The need to balance input and output of organic material between a farm and adjacent ecosystem was demonstrated. The importance of developing fish production systems that recycle nutrients into other valuable end products to conserve resources and maintain the environment (Adler *et al.*, 1996; Adler, 2000; Hankins 2000) was also made apparent by this pioneering effort.

An example of nutrient recycling in tilapia culture is the integration of RAS with hydroponic vegetable production, a technology called aquaponics (Rakocy, 1997). A large portion of waste nutrients generated by fish is recovered by high-value vegetables (e.g., tomatoes lettuce and cucumbers), which improves the profit potential of the system. The vegetable component assimilates nutrients, purifies the culture water, and eliminates the need for separate biofilters. Savings are also realized by sharing operating and infrastructural costs. Aquaculturists frequently mention the possibility of incorporating hydroponics into closed RAS to mitigate waste discharge and earn extra income. However, properly designed aquaponic systems emphasize plant production, which receives about 90% of the culture area and generates 65 to 70% of the revenues (Rakocy, 1997). In other words, the properly designed integrated fish/aquaponic farm produces a high ratio of plant to animal products. Hence, stocking fish at high densities ($> 100/m^3$) and using pure oxygen systems are not practical or cost effective. Data from successful, large-scale trials are needed to attract investor capital and commercial development. The immediate potential for aquaponics systems is niche markets where consumers pay higher prices for consistent high-quality fish and specialty crops. Due to water reuse efficiency, aquaponics systems have considerable potential in arid and semiarid areas and in tropical and subtropical island communities.

Another example of nutrient recycling in tilapia culture is to rear tilapia in tanks or raceways, using effluent to irrigate and fertilize halophytes, or salt-tolerant plants for human and animal consumption. A number of species of salt-tolerant plants with potential as forage and oil seed crops have been found to effectively remove nitrogen and phosphorus from effluents from an intensive tilapia culture system (Brown *et al.*, 1999). In Mexico, tilapia are being experimentally grown in saltwater in polyculture with the macroalga *Gracilaria* (Fitzsimmons, 2000a), an edible seaweed. Gracilaria are placed in a sequential polyculture after a tilapia rearing tank so that it is fertilized by fish wastes.

K. IMPROVED FILTRATION DESIGN AND EFFICIENCY OF RAS

As aquaculture production continues to intensify in the future, the use of intensive recirculating systems will expand. Concerns over effluents are helping drive this trend, even in areas with access to warm water supplies. In the U.S., intensive indoor RAS tilapia culture is constrained by high capital and operating costs, moderate growth rates, poorly utilized production capacity and consequent low system throughput. Advances in filter design and construction hold promise for reduced capital and operating costs for RAS in North America.

L. MARKETING

While definitive data on the economics of tilapia aquaculture production systems are lacking, a clear trend toward higher production costs in the U.S. and Canada than in Central America, South America, or the Caribbean is attributable to many factors. The costs of high-quality feeds are comparable in the U.S. and tropical countries, but tropical producers have lower energy costs because they do not require heating, and farms are generally designed to avoid pumping water. Labor costs are lower and water treatment is not necessary, as most are flowthrough with no treatment of wastewater. Regulatory costs for disposal of offal and wastewater are higher for U.S. producers (Hargreaves and Behrends, 1997). Land costs are lower in tropical countries and lease space in lakes represent a small part of production costs.

Indoor RAS exhibit economies of scale, with larger systems producing at lower costs (Engle, 1997a). Large producers require a large processing sector that also has economies of scale, but overall market demand must be adequate to absorb the output. Hence, in the absence of a tilapia processing sector, tilapia growers have relied on live and niche markets, which bring the highest prices. A significant challenge for the tilapia industry is this paradox in which existing markets can handle only small quantities at a time, but economies of scale favor larger systems (Engle, 1997a). The commercial production of tilapia in Canada and the U.S. therefore is limited to the higher priced, mainly Asian and Hispanic live fish markets in large metropolitan areas (LA, San Diego, SF, Vancouver, Houston, New Orleans, New York, and most importantly Toronto). These markets are becoming saturated. U.S. producers need to develop live markets in untapped, smaller cities and outside traditional Asian cultural groups to wider ethnic and socioeconomic groups. Grocer stores and restaurants with live tanks, and local farmer markets are the most likely sectors to expand. Restaurants and seafood counters are the more traditional outlets and entry to these markets will present tilapia to a much larger consumer base. However, North American growers must eventually enter the fillet market if production is to continue to expand. Given the cost advantages enjoyed by tropical producers, this will be a major challenge.

It has been suggested that U.S. producers can overcome the competitive advantage enjoyed by tropical producers by optimizing resource utilization. The production of large stocker fingerlings in ponds fertilized with nutrient and organic matter generated by poultry producers, enhanced growth through waste heat utilization and improved genetic stocks, and improved production management to effectively utilize system capacity may improve overall economic feasibility in the U.S. (Hargreaves and Behrends, 1997; Lutz, 2000). The economies of scale may favor production by large, well-funded, vertically integrated operations (Timmons and Aho, 1998). The initiation of this in the U.S. is seen in the company Southern States, a farmer-owned cooperative operating in 16 states from Michigan to Florida and west to Los Angeles. Based in Richmond, Virginia, this firm is one of largest U.S. farmer-owned cooperatives that purchases, manufactures or processes feed, seed fertilizer and fuel. In the southeastern U.S., growers in the Southern States Program Cooperative receive fingerlings, feed and technical support from the co-op, which purchases, processes and markets the tilapia produced.

History has shown that with decreased availability of fish, consumers will readily turn to other dietary substitutes. In 1961, Jamaica had a per capita rate of fish consumption of 33 kg/year, one of the highest in the Caribbean (FAO, 1992). By 1990, this had declined to 16 kg due to an overfished marine fishery, shortage of foreign exchange for fish imports, the increased production of substitutes (notably poultry), and an increasing population. This emphasizes the importance of continuing to improve the market demand for fish products such as tilapia.

The continued growth of the tilapia industry in the Americas will depend on improving production efficiency and quality control to maintain competitive prices. Sizing, more diverse product presentation, packaging, and shelf-life will be critical in this regard. In addition, there is a widespread consensus on the need for a strong marketing program to sustain industry growth. Marketing campaigns to obtain better prices for live or fresh tilapia over frozen imported can contribute to economic stability in the Americas. Marketing efforts should be directed toward increasing public awareness of tilapia, with an emphasis on price, quality, nutritional characteristics, and availability (Fitzsimmons, 2000c,e).

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