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EXOTIC SPECIES IN GLOBAL AQUACULTURE - A REVIEW

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Abstract

The culture of exotic fishes contributes about 17% to global food aquaculture production. Transplanted native species add substantially to the aquatic harvest of food and sport fishes in many countries. Some countries are very dependent on the cultivation of non-native species; yields of exotics exceed 25% of the total harvest in China, 60% of the freshwater harvest in the Philippines, and 50% of the production in Brazil. Aquatic food production in Israel is predominately from introduced fishes. In the USA, transplanted species are economically important as food and sport fish and exotics are used in resource management as well as a major food source. Countries of origin for globally important fishes include China (endemic carps), USA (Atlantic salmon and rainbow trout), Europe (common carp), and Africa (tilapias). The aquaculture production of food fish will become increasingly vital as oceanic capture fisheries continue to stagnate. Exotic and transplanted fishes that are widespread today will represent a greater proportion of future aquaculture production because technology for their culture is already well known and can readily be applied, and because these species are more easily domesticated and genetically improved.

Introduction

Plants and animals have been moved from one area to another for centuries. Food crops and domesticated animals have been developed and dispersed worldwide in association with man's resettlement. Humans have been integral in translocations of food crops to new areas outside their natural range. Such companion plants and animals have been greatly modified from their native ancestral types through passive selection and active breeding programs. Non-native domesticated and cultivated terrestrial organisms are generally not perceived as exotic but, rather, as part of the natural landscape. However, this does not

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usually apply to aquatic species. Non-indigenous fishes are commonly considered aliens or invaders.

The concept of exotic organisms should be more precisely defined, especially within the context of aquaculture. The following terminology is based on Shafland and Lewis (1984). A species is considered ‘native’ or ‘indigenous’ with reference to its historically natural range. A fish that has been intentionally or accidentally moved outside its natural range is defined as ‘introduced’. Introduced fishes can be either ‘transplanted’ by man between watersheds within the area of origin (Lachner et al., 1970) or ‘exotic’ if the transfer is between areas. Introduction generally implies release or escape of an exotic or transplanted species into a natural ecosystem. Confinement in a commercial or research facility can also be considered introduction, because escape is probable (Shelton and Smitherman, 1984). Other somewhat synonymous terms include alien, non-native, and invader (Lever, 1996). If reproduction and recruitment occur, fish are considered ‘naturalized’ or ‘established’. The purpose of this paper is not to defend the use of exotic fishes nor discuss potential impacts from introductions, but to focus on their importance in aquaculture.

All agricultural crops are exotic cultivars and all domesticated animals are products of a long history of selection. Grains originated in the Middle East and many vegetables have derived from South American plants. Agricultural practices evolved over centuries and have been adapted to various climates and economies so that, now, non-native organisms are fully accepted. Animal husbandry is based on a handful of exotics; four omnivorous mammals and four herbivorous birds form the basis of modern animal culture. On the other hand, about 131 finfish species are commonly cultured, and few have been selected to any degree. Non-native fishes represent differing degrees of aquaculture production in different countries, although not to the extent that exotic cultivars and breeds are used in agriculture and animal husbandry. Their importance is increasing, however, particularly because of the developing shortfall in capture fisheries.

Aquaculture is the farming of aquatic organisms for food, sport, conservation, or ornamental purposes. Artificial propagation is a vital component of contemporary aquaculture since it ensures a supply of seed stock for grow-out, enables selective breeding for stock improvement, and facilitates transfer and maintenance of species outside their native range. While the culture of non-native species has multiple benefits, it may also have complications.

Aquaculture has been practiced for over 3,000 years, but improvements through the application of scientific principles are relatively recent (Wohlfarth and Hulata, 1989; Billard, 1995). Most adaptive practices for economically important species have been incorporated within the past four to five decades, during the same period that sensitivity to environmental issues has grown, particularly in industrialized countries. Thus, aquaculture was compelled to develop under a burden of ethical and environmental constraints that did not restrict the formative period of agriculture. Restricting fish farming to the culture of native fishes within their historic ranges represents a serious constraint to aquatic food production.

Many fish species have been moved outside their native range but relatively few have been widely dispersed. The earliest species to be relocated were the common carp, goldfish, and, somewhat later, rainbow trout. The common carp was transplanted at the beginning of the sixth century from its native range in the lower Danube River, westward into Europe, eastward into China, and southward into Italy (Wohlfarth, 1984; Balon, 1995). Several cultivated breeds of common carp are now recognized. They have characteristics that are qualitatively and quantitatively different from ancestral stocks, but are considered only marginally domesticated (Hulata, 1995). The development and transfer of the many varieties of goldfish date from the late 1100s to the mid-1600s. Rainbow trout transfers did not begin until 1874 (Gall and Crandell, 1992), but contemporary dispersal is nearly as far-flung as that of common carp (Brannon, 1991).

Global introductions of aquatic species have increased throughout the twentieth century (Bartley and Casal, 1998). A total of 1,354 introductions of 237 species into 140 countries have been recorded. However, relatively few species are widely distributed and only 10-13 species were introduced into more than ten countries. Ninety-eight exotic species have been introduced for aquaculture and 78 for sport fishing, not including widespread transplanting within countries for culture or sport fishing. A total of 321 introductions (24%) resulted in established populations, but over 298 (22%) of the introductions did not become naturalized. Only 89 (7%) had sufficient impact to cause serious concern, while the other 232 (17%) were judged to be neutral or beneficial (Welcomme, 1988).

Many introductions within the U.S. have involved transplants of native species, two-thirds of which have been for sport fisheries; 71 species have been established and 38 of these have been related to the aquarium trade (Fuller et al., 1999; Nico and Fuller, 1999). The rate of exotic transfers has increased since about 1945, somewhat in conjunction with the development of artificial propagation techniques (Welcomme, 1984). Worldwide, exotic transfers (Table 1) have occurred in four general waves: (a) prior to 1900, movement primarily involved salmonids; (b) in the early part of the twentieth century, common carp was disseminated; (c) just after the mid-20th century, tilapias were commonly transferred; and (d) most recently, during the 1960s and 70s, Chinese carps were moved. More than in any other group, developments in induced spawning provided the means to expand the culture of Chinese carps to new areas, even within southeast Asia (Zonneveld and Van Zon, 1985; Horvath et al., 1992; Rothbard and Yaron, 1995).

The global growth rate of agricultural products has been slowing. The overall increase was about 3% per year in the 1960s but only 1.8% in the 1990s, with an average of about 1.4% during 1970-2000. In 2000, global production of pork was 90 million tons, beef 57 million tons, and poultry 58 million tons (Table 2). Harvest from capture fisheries has been generally static at around 95 million tons (1.4% growth). In contrast, farmed fish production has grown at an average annual rate of 9.5% in the period 1970-2000 (FAO, 2002).

Table 1. Major fish introductions during the twentieth century.

Species	*No. introductions*
Common carp	124
Rainbow trout	99
Mozambique tilapia	92
Nile tilapia	80
Silver carp	79

If aquaculture is to make up for the expanding aquatic food deficit associated with the current capture-fisheries shortfall, if it is to provide biocontrol options in natural resource management, and if it is to reduce overexploitation of ornamental fishes in their native range, then introduced species must be recognized as a necessary option for managed production in aquatic systems. Statistics on exotics are not always available, therefore much of the present discussion uses examples from selected countries.

Status of Aquaculture

Animal protein from aquatic sources is important for human nutrition. Worldwide commercial harvest was about 98 million tons in 1991 with about 70% being used directly for human consumption (Thorpe et al., 1995) and 20-30% rendered to produce fishmeal and oils for use in animal feeds. Potential world production of aquatic organisms from all sources is estimated to be 100-150 million tons (Table 3). Capture fisheries are no longer sufficient to maintain the required supply of aquatic food; in fact, harvest has already entered a period of decline (Allsopp, 1997; Garcia and Newton, 1997). During the 1950s and 60s, world capture fisheries increased about 6% per year but it slowed to about 2% per year in the 1970s and 80s, then flattened in the 1990s (FAO, 2000). About 60% of marine fish stocks have

Table 2. Global animal food production in 2000[a].

Source of animal protein	*Production (million tons)*	*Annual growth rate (%)*
Pork	90	3.1
Beef[b]	57	1.3
Poultry	58	5.1
Capture fisheries[c]	96.1	1.4
Aquacultured species[d]	29	9.5
Cyprinids	10.4	10.0
Salmonids	1.9[e]	10.6
Cichlids	1.3	13.5
Catfish	0.4[f]	9.4

[a] Tacon (1997, 2003); FAO (2002).

[b] 54% of livestock meat is produced in developed countries while over 83% of fish is produced in developing countries. Per capita fish consumption is 15.7 kg throughout the world and 7 kg in the USA.

[c] Ninety percent of capture fisheries are marine fisheries, 6% of which are depleted, 16% of which are overfished, and 44% of which are fully exploited. Only 3% are recovering under management.

[d] Exotics make up about 17% of world production. Aquaculture contributes an average of 23% to aquatic production. Freshwater finfish make up about 46% of total production.

[e] Includes 0.7 million tons Atlantic salmon and 0.5 million tons rainbow trout caught in the wild (capture fisheries).

[f] Includes 300,000 tons channel catfish and 150,000 tons Pangasian and other catfishes

been depleted, over-harvested, or are fully exploited. Over the past 45 years, landings from global fisheries have shifted from large piscivorous species toward smaller planktivorous fishes and, in recent decades, the slight expansion of harvest was possible only through increased fishing efforts (Pauly et al., 1998). Inland capture fisheries make up only about 6% of the total exploitive supply but represents about one-third of the total freshwater production. Some inland capture fisheries are facilitated or totally dependent on fish culture to replenish stocks.

Aquaculture has followed a different trajectory from oceanic fisheries. In the 1950s and 60s, foodfish production grew by about 5% per year. In the next two decades, it grew by 8% annually. Worldwide aquaculture production steadily increased in recent years by about 15% per annum. The growth in total aquatic supply in the 1990s has been almost entirely due to increases in aquaculture and the greatest contribution has been from the rapid expansion in Chinese freshwater culture (Lu, 1997). Worldwide production in 1992 was 15-17 million tons with 84% produced in developing countries, including 51% finfish, 20% mollusks, 4% crustaceans, and the rest plants and other products (Thorpe et al., 1995). Total production in 1994 was estimated at 18-20 million tons, 23% of the total world aquatic yield (New, 1997). Culture grew to 28-

Table 3. Aquaculture and capture fisheries, marine and freshwater (million tons)[a].

Source	*1990*	*1995*	*2000*
Aquaculture	13.1	24.6	45.4[b]
Inland	8.0	14.1	21.4
Marine	5.1	10.5	23.0
Capture	86.4	91.5	94.8
Inland	6.3	7.2	8.8
Marine	80.1	84.3	86.0
Total	99	116	140

[a] Born (1999); FAO (2002).

[b] Total production = 50.4% finfish, 23.5% mollusks, 22.2% aquatic plants, and 3.6% crustaceans. Freshwater: 76 species, 97.7% production from finfish. Marine: 35 species; 8.7% production from finfish, 46% from mollusks, 44% from plants.

39 million tons in 1999 and over 45 million tons in 2000 (FAO, 2002).

About 300 species are grown in aquaculture but only 131 are produced in significant quantity. Thirty-two species contribute 0.1-1 million tons, each, to annual production while only six to eight exceed 1 million tons (Table 4). The top five finfish species in aquaculture are carps, and tilapia is sixth. Carps and tilapias are the most important groups in global fish culture (Borgstrom, 1978). Of the 18.5 million tons of aquaculture production in 1994, carps constituted 42% (New, 1997). Much of the increased production resulted from worldwide transplanting of carps, tilapias, catfishes, and salmonids into new geographic areas (Allsopp, 1997). The greatest production of carps is in southeast Asia where most species are indigenous although transplants became common as a result of developments in artificial propagation of Chinese carps. Almost all tilapias are cultured outside their native range. Since capture fishery supplies are overexploited and current harvests are static at best, aquaculture must continue to expand at a high rate to meet the growing demand for aquatic products.

Non-native Fishes in Aquaculture

China. China dominates world aquaculture (Table 5). While global production increased by 0.4-0.7 million tons per year until 1992, productivity in China increased by about 2.6 million tons per year. In 2000, aquaculture in southeast Asia was about 90% of the total and over 70% was produced in China alone (FAO, 2002; Tacon, 2003). Despite the long history of aquaculture in this region, the tremendous growth in production during recent decades has been due to increasing emphasis on freshwater culture. In the late 1990s, mainland China had a total of 18 million hectares of inland water, which included 7.4 million of lakes, 6.8 million of rivers and canals, 2 million of reservoirs, and 27 million of paddies (Marttin, 2001). Pond culture produced about 67% of the total inland yield, while reservoir production (culture and capture) produced about 9%. Traditional polyculture is common in China, but more extensive reservoir ranching systems also raise multiple species (Li, 1986; Li and Biyu, 1990). There are about 85,000 reservoirs that are usually stocked with species, such as silver, bighead, and

Table 4. Culture of primary finfish in selected years (million tons), principal producers, % of global production, and origin of species in 2000[a].

Species	*1990*	*1995*	*2000*	*2000 (country, % of global production, origin of species)*
Silver carp	1.5	2.5	3.5	China, 97, native/transplant
Grass carp	1.0	2.1	3.4[b]	China, 98, native/transplant
Common carp	1.1	1.8	2.7	China, 78, native/transplant
Bighead carp	0.7	1.1	1.6	China, 98, native/transplant
Crucian carp	0.2	0.5	1.4	China, 98, native/transplant
Nile tilapia	0.2	0.5	1.0	China, 67, exotic; Philippines, 13, exotic
Atlantic salmon	0.2	0.5	0.9	Norway, 57, native; Chile, 12, exotic
Rohu carp	—	0.5	0.8	India, 83, native/transplant
Catla carp	—	0.4	0.7	India, 99, native/transplant
Mrigal carp	—	0.4	0.6	India, 99, native/transplant
Rainbow trout	0.3	0.4	0.4	Norway, France, Denmark, Chile, Italy, 11-16 each, exotic

[a] Tacon (2003).

[b] Does not include fishes produced for aquatic weed management. In USA, 1 million produced per year @ $2-4, each, for a total value of about US$3 million.

grass carp, that do not reproduce under lentic conditions. Silver and bighead carp make up 60-80% of the stocked fish. Over 40 freshwater species are commonly cultured in China, but four species together account for about one-third of the total yield.

Exotic species contributed about 17% to the overall global production of aquatic species at the close of this millennium (Bartley and Casal, 1998). By early 1990, sixty exotic species had been introduced into China (Lu, 1997; Cen and Zhang, 1998). Native carps are the primary crops in China, but there has been considerable transplanting. Exotic and transplanted species make up to 25% of the total yield. In addition, 88 tropical exotic fishes are cultured for the ornamental fish trade. Exotic species cultured for food include tilapia, rainbow trout, paddlefish, roach, and channel catfish (De Silva, 1989; Li and Mathias, 1994; Lu, 1997). Tilapia production increased from 9,000 to 120,000 tons in the 1980s and export subsequently expanded; 5,000 tons of frozen tilapia were sent to the USA in 1999 (New, 2001). The North American paddlefish will be a valuable addition to Chinese reservoir ranching. Like the native bighead, it is a filter-feeder and a riverine spawner, and thus will require artificial propagation, but it does not have intramuscular bones. The paddlefish was introduced from the USA to the former USSR in 1974 and is now being raised commercially with fertilized eggs being supplied to other countries, including China (Vedrasco et al., 2000).

India. Currently, India is the world's second

Table 5. Aquaculture production by country in 2000[a].

Country	*Rank*	*Production (million tons)*	*Exotics/transplants (thousand tons)*	*(%)*	*Comments*
China	1	32.4	8,100	25	109 exotics and transplants; 45% are cultured; 88 ornamental species
India	2	2.5 inland; 5.8 total	-	90	3 exotic carps, 4 native carps and tilapias
Philippines	4	1.0	63 tilapia	60	3 of top 5 freshwater species are exotic
Thailand	9	0.7	10 tilapia	7	-
USA	11	0.4	grass carp[b]; striped bass[b]; 5.9 hybrid bass; 6.8 tilapia	10	38% of sport fishes are native transplants[b]; hybrid striped bass raised for food and sport
Chile	13	0.4	300 salmonids[c]	70	All exotic trout/salmon
Brazil	18	0.2	25 tilapia; 2 trout; channel catfish	50-75	Transplants and 7-10 exotics
Israel	-	0.02	6.4 tilapia; 7.4 carp; 0.5 trout; 0.2 hybrid bass	39; 47; 4; 1	Ornamentals - US$12-15 million/y; 40 introduced species
Malaysia	-	-	0.4 tilapia	64	-
Cuba	-	-	0.03 tilapia; 0.03 Chinese carps	95	4 of 6 major species are exotic

[a] Ang et al. (1989); Lovshin and Cyrino (1998); Martinez and Pedini (1998); Golani and Mires (2000); Guerrero (2000); Lovshin (2000); Brugere and Ridler (2004); Snovsky and Shapiro (2004).

[b] Not including: (a) striped bass stocked in 456 inland reservoirs and hybrids in 256 reservoirs for multimillion dollar sport fishery, (b) grass carp stocked for weed control, 1 million/year valued at US$3 million to producers, for history of introduction see Opuszynski and Shireman (1995), Cassani (1996), and Mitchell and Kelly (2006).

[c] Chile is world's major salmonid producer, all exotic including Atlantic salmon (107,000 tons), coho salmon (76,000), and rainbow trout (75,000).

largest fish producer. Aquaculture in India is based primarily on pond polyculture of native major carps supplemented by Chinese carps. India's rohu, catla, and mrigal yields were the eighth, ninth, and tenth largest yields in the total world finfish production (Table 4). In the 1960s, India added grass carp and silver carp from China to their polyculture of native carps in a system called composite culture (Bhimachar and Tripathi, 1967; Singh et al., 1972; Nandeesha, 1995). Total yield has reached 5.8 million tons of which 3 million are from mariculture and marine capture fisheries and 70% of the remaining 2.5 million tons is from inland fisheries, 90% of which (1.6 million tons) is based on carp culture (Gopakumar, 2003). Composite culture is used in traditional pond stocking, but also to supplement reservoir capture fisheries (Jhingran, 1986). Introduction of the Mozambique tilapia to Sri Lanka in the 1950s and the Nile tilapia in the 1970s developed into major capture fisheries in reservoirs (Balayut, 1983).

Philippines and Far East. The Philippines was the world's fifth largest producer of aquaculture products (957,000 tons) in 1997 and freshwater aquaculture was responsible for 29% of the total yield (Guerrero, 2000). Milkfish production in brackish-water ponds was 148,000 tons. Only 11% of the total production (105,000 tons) was from fresh water; 39,500 tons were produced in 14,500 ha of ponds and 52,000 tons in cages and pens. Over 200,000 tons were finfishes, and three of the top five were exotics (Nile tilapia, bighead carp, African catfish), accounting for most of the freshwater production. Nile tilapia is now the main food fish (63,000 tons). Taiwan and Thailand are also major producers of Nile tilapia in southeast Asia with over 100,000 tons each (Ang et al., 1989; Shelton, 2002).

Aquatic Ranching

Fish ranching, based on hatchery propagation, stocking of juveniles in open systems, and natural fertility, is a form of extensive aquaculture. Balayut (1983) discussed some of the failures to establish fisheries by stocking exotics in reservoirs of southeast Asia.

The ranch concept has been applied to several carp and tilapia species in inland reservoirs in China and India, as well as to salmonids in oceanic systems. In India, native carps and exotic Chinese carps are stocked together in traditional pond culture and to supplement reservoir capture fisheries (Jhingran, 1986). Chinese carps have been stocked in 49 Cuban reservoirs ranging 10-10,000 ha since 1974 (Quiros, 1998).

Tilapias have been widely introduced to establish capture fisheries in Brazil, Sri Lanka, and Africa (Lake Victoria). In Sri Lanka, Mozambique tilapia stocked in reservoirs in the 1950s and Nile tilapia in the 1970s provide major capture fisheries (Fernando, 2000).

Reservoir ranching is also used for Chinese carps within China, often as transplanted introductions. While pond culture is the primary production system (67% of the total inland yield), reservoir ranching accounts for about 9% (Li, 1986; Li and Biyu, 1990). Many reservoirs are stocked with silver, bighead, and grass carp.

The caviar industry in the Black and Caspian Seas was maintained for decades by ranching transplanted sturgeon (McNeil, 1979). About one-third of the capture harvest in the Caspian Sea was from hatchery-produced and released fish. The breakup of the USSR affected propagation and reduced the capacity to regulate harvests, thus sturgeon fisheries are now in a rapid state of collapse (Khodorevskaya et al., 1997).

USA - Exotics

The first half of the 1800s was an active period for fish transfer in the USA (Table 1). Fish were largely cultured by government agencies for restocking, exotic fishes were stocked, and native species were transplanted. Atlantic coast striped bass was introduced to Californian coastal waters and rainbow trout and Pacific salmon were disseminated outside their natural range to the east. Common carp was the first recorded exotic fish to be introduced in the USA, followed by the European brown trout. Brown trout has been stocked in 33 states as a sport fish and is generally considered a positive addition; there is virtually no contemporary foodfish culture of this species in the USA (Courtenay and

Kohler, 1986). At the same time, rainbow trout was being exported from the USA to other countries. Today rainbow trout has been introduced in 44 countries and is nearly as widely dispersed as carps and tilapias. Also, many centrarchids were exported to numerous countries and, more recently, paddlefish, buffalofish, and channel catfish have been exported to Russia, China, and ten other countries.

Tilapias were imported to the USA in the 1950s and 60s. Chinese carps were imported in the early 1960s. Forty-six species have been transferred to North America of which 39 were considered established by the early 1980s (Courtenay et al., 1984). The USA now has at least 70 established exotic species (Courtenay and Kohler, 1986; Courtenay, 1995), 23 of which are established in Florida and all but three introduced to the aquarium trade (Shafland, 1996).

The most widely cultured crustacean in the world is the giant freshwater prawn. It was introduced in Hawaii in the mid-1960s and by 1988 was a US$18.2 million crop. Most prawn culture is in the Indo-Pacific (Davidson et al., 1992). In the USA, the Pacific oyster is cultured primarily in the northwest where it was imported early in the 1900s to supplement dwindling stocks of native species (Chew, 1979). Culture of the Pacific oyster in the USA now makes up about 56% of the world production and about 40% of the 20,000 tons of oysters marketed in the USA (Burrell, 1985; Matthiessen, 1991). The Pacific oyster was exported from the USA to Britain in 1965.

USA Transplants - Food Fish

The perception of exotics and transplants in North America is somewhat relative. Transplanting natives or using exotics in sport fisheries is more readily accepted than using exotics for food production or natural resource management.

Channel catfish. Relatively few exotics are grown as food fish in the USA but many native species are cultured outside their original range. Some critics of exotics in aquaculture have suggested that native species should be preferentially used. In fact, the endemic channel catfish and rainbow trout are the primary cultured species in the USA, although a significant amount is produced outside native waters (Tables 6,7). Ninety-seven percent of catfish are cultured in five southeastern states within its native range but about 2% come from introduced stocks in California (USDA, 1990; Courtenay, 1995). Pond culture is the predominant system for raising channel catfish. In 2000, over 300,000 tons were harvested from about 130,000 ha of freshwater ponds at a value of over US$600 million (USDA, 2001).

Rainbow trout. Most domestic culture of rainbow trout (50-75%) is within the trouts' natural range in the Snake River Valley of Idaho but about one-third are grown elsewhere in the USA (Parker, 1988, 1989). The value of USA production is US$82 million (Table 8). Food-size fish accounted for 84% of trout sales in 1999 (USDA, 2001). The development of artificial propagation of salmonids in the mid-1800s initiated a period of movement of both transplants within the USA and introductions to other countries. Denmark received rainbow trout in 1870 and soon established commercial facilities; its production reached 350,000 tons in 1998. Contemporary domestic rainbow trout production is relatively insignificant in comparison to yields elsewhere. Rainbow trout are currently grown in 40-55 countries and is the second most important freshwater salmonid produced for food (Tables 5, 6). Harvest in the USA and five European countries was 16,000-25,000 tons, each. Yield in Chile was about 52,000 tons in 1997 but, in 2000, Chile, Denmark, France, and Italy were major producers with 40,000-50,000 tons each (Novotny and Nash, 1995; Steffens, 1997; Martinez and Pedini, 1998; IntraFish, 2001).

Striped bass. Another important endemic species now cultured in the USA is the striped bass, an anadromous Atlantic coast species that has been exploited in both sport and commercial capture fisheries. It has been widely transplanted; the first introduction was on the west coast of the USA in 1871-1881, resulting in a naturalized sport fishery. In the 1940s, a land-locked reproducing population was found

Table 6. Principle exotic species cultured in 2000[a].

Species	*Global production[b] (thousand tons)*	*Major producing countries*	*Production (thousand tons)*	*Proportion of global (%)*
Chinese carps	8,500	China[c]	8,300	98
		plus 30-50 others	–	–
Common carp	2,700	China	2,100	78
		plus 70 others	10-11	–
Tilapia	1,300 Nile	China	850	60
	>73 Mozambique	Thailand	28	–
		Taiwan	20	–
		USA	7	Imports 90 tons
		Israel + 70 others	5	–
Atlantic salmon[d]	700-860	Norway	420	–
		Scotland	125	–
		Chile	103 + 39 coho	–
		USA	15	Imports 95 tons
Rainbow trout[e]	450	Four countries	50 each	–
		USA	26	–
		Five others	26 each	–
		plus 31 others	15	–
Channel catfish	300	USA	250	70
		plus 10 others	–	–

[a] Steffens (1997); Tacon (1997); Martinez and Pedini (1998); FAO (2002).
[b] Global production of exotic fishes is about 17% of total aquaculture; freshwater fish = 87% of total, carps = 70%, tilapias = 5%.
[c] Not all Chinese carps in China are cultured within their native ranges.
[d] Salmon caught in the wild equaled 700,000 tons.
[e] Chile, France, Italy, Denmark produce 45,000-50,000 tons each; six other countries produce 25,000 tons each. All are exotic except in USA where 35% are cultured outside native range.

in a freshwater reservoir on the Santee-Cooper River, South Carolina. This discovery stimulated studies on artificial propagation techniques and a successful protocol was developed in the early 1960s. Hybridization with the freshwater white bass was also investigated (Harrell et al., 1990). During this period, the natural anadromous populations were declining because of habitat alteration and over-harvest (Richards and Rago, 1999) and a total fishing ban resulted in the development of interest in culturing for restoration as well as farming for food. A hybrid was found to be more suitable for foodfish culture than the parentals. The original cross used female striped bass and male white bass (palmetto bass). A hybrid with

Table 7. Important species in the USA (thousand tons)[a].

Species	*1990*	*1995*	*2000*
Channel catfish	163	203	300
Tilapia[b]			
US produced	-	6.9	8.1
Imported	-	22.0	40[c]
Global	391	705	1,100-1,350
Trout			
USA[d]	25.7	25.2	26.9
Global	-	357	450

[a] MacIntosh and Little (1995); Engle (1997); Green et al. (1997); New (1997); USDA (1998, 2001); Stickney (2005).

[b] About 70% of global cichlid production was Nile tilapia. Import data is subject to variation because some weights are weights of fillets instead of live weight equivalents (fillet is about 20% of live weight). Capture fisheries harvest was about 227,000 tons in 1992, 44% of which was from Lake Victoria in Africa.

[c] 90,000 tons imported from China in 2003.

[d] About 30% of rainbow trout cultured in USA is grown outside the native range.

white bass females was subsequently tested and this reciprocal cross (sunshine bass) is now widely cultured. USA foodfish production was estimated at 450 tons in 1989 and 5,900 tons in 2000. In 1987, 152 tons were produced in California, outside the natural range of both parental species (Kerby and Nash, 1995; Woods et al., 1995; Webster et al., 2002). Striped bass and hybrids are also very important in sport fisheries.

USA Transplants - Sport Fish

Sport fishing in the USA is recreationally and economically important. Fifty million Americans fish each year, generating US$69 billion (Radonski and Martin, 1986). Stocking is important to sport-fishery management, and fish culture is the foundation that supports the entire infrastructure. Stocking programs depend on culture in federal or state government hatcheries although private farms have assumed an increasingly important role. More than 200 species, predominately transplanted native North American species, have been stocked in public and private waters for sport fishing in North America (Bensen, 2000). In the early days of fish culture in the USA, hundreds of millions of fry were produced and the public accepted widespread stocking as a primary management tool.

Stocking exotic fishes is a comparatively small segment of sport fisheries. Most exotics tried as sport fishes in the USA did not develop into lasting fisheries (Radonski et al., 1984). While supplemental stocking of native species has proved largely ineffective, transplanting native fishes into new areas has produced good results. In recent years, transplant stocking has been vociferously opposed by some, even in reservoirs which by nature are altered habitats. Colorado River reservoirs are particularly poignant examples. The closure of the Hoover Dam in 1935 resulted in drastic changes to the habitat and much unique

Table 8. Economic value of select species aquacultured in the USA in 2000.

Species	*Economic value (million US$)*	*Comments*
Catfish	600	Most cultured within native range; widely stocked
Tilapia	101	Major import; 40,000 tons
Trout	82	About 35% cultured outside native range; widely stocked
Bait fishes	71	Minnows and goldfish
Ornamental	68	Exotic species cultured in southeast; dispersed widely
Striped bass/hybrids[a]	28	Includes 5,900 tons of cultured hybrids; value of sport fishery not included
Grass carp[b]	2-6	One-million fish produced annually for weed control

[a] Value of striped and hybrid bass recreational sport fisheries is in the multimillions. Bass are stocked throughout the USA in inland reservoirs, all are transplanted. Foodfish culture consists primarily of the sunshine bass hybrid.

[b] Grass carp culture is primarily for stocking 4-6 cm fingerlings for weed control. Approximately 150,000 2N and 500,000 3N are produced annually @ $3-5 each.

endemic fauna began to decline (Courtenay and Robins, 1989). The newly created reservoir stimulated the introduction of an array of predator and prey species; eleven were subsequently transplanted into the system. While habitat alteration established the basis for the decline of indigenous species, the primary blame for the demise of the endemics is usually placed on the stocked non-native fishes.

More than 206 species occupy waters in the USA outside their native range (Courtenay, 1995); 75% were introduced as sport fish. Forty-nine of the 50 states have used non-native sport fishes in their management programs. Fishing for non-native species has supplied 40-75% of the angling efforts over the past 50 years. Thirty-six percent of the states have fewer native than introduced sport fishes and, on the average, non-native fishes provide about 38% of the states' recreational fisheries (Horak, 1995). California epitomizes the significance of transplanted fishes for sport fisheries. The native fauna of California lacks most of the important North American sport species, including centrarchids, ictalurids, and percichthyids. Only ten inland species native to California are considered sport fish. During the past 125 years, 30 non-native fishes have been introduced for recreational purposes (Lee, 1995).

After the decline of the native trout fishery in Lake Michigan, coho and chinook salmon were introduced from the Pacific. Rainbow trout have been stocked in every state in the USA for recreational fishing, but annual stocking is required in most areas (Fuller et al., 1999). Rainbow trout have been used far outside their natural range in some warm-water reservoir two-story fisheries, as well as in the streams below dams. Continued stocking is required to maintain these fisheries (Wilkins et al., 1968; Jones, 1982).

Striped bass introductions have been phenomenally successful and are widely disseminated in inland waters. Stocking striped bass in inland reservoirs was not possible until induced-spawning techniques were developed (Harrell et al., 1990). This technology not only permitted testing hybrids as an alternate sport fish but also provided the impetus for their culture as a food fish. The foodfish industry and most recreational fisheries for striped bass are totally dependent on artificial propagation. Beginning in the 1960s, reservoirs throughout the USA were stocked with striped bass, resulting in countless hours of recreational fishing and millions of dollars of increased revenues (Whitehurst and Stevens, 1990). A single naturalized and self-sustaining population in Lake Texoma, Oklahoma-Texas, was estimated to have contributed US$25 million to the local economy in 1990 alone (Schorr et al., 1995). Atlantic coast striped bass have been introduced into more than 450 inland reservoirs in 36 states since the mid-60s (Stevens, 1984). Hybrids also have been introduced into 264 reservoirs. About 2.3-million ha have been stocked (Kerby, 1986). In all but about ten naturalized populations, annual maintenance stocking by the state is required to support the fisheries. This example illustrates the general acceptance of transplanted sport fishes, an attitude not usually accorded to exotic species in aquaculture or resource management.

A vital but often overlooked component of fish culture for sport fisheries is the production of baitfish. About 11,000 tons of baitfish were cultured in the mid-1980s, ranking third in value behind catfish and trout (Parker, 1988). The annual farm-level sales of baitfish, not considering retail sales to anglers, was about US$71 million in the mid-80s (Table 8). Seventy-one percent of the minnows are produced in Arkansas and widely dispersed as live bait (Rowan and Stone, 1996). While this culture supports sport fisheries, the use of live baitfish itself can be a source of transplanting. “Bait-bucket introductions” have been indicated for 58 species transplants in the USA (Courtenay, 1995).

USA - Exotics in Resource Management

Relatively few fish species have been introduced in the USA for biological control, but few other activities have elicited such conflict. The USA National Academy of Science (NAS) proposed that biological control of nuisance aquatic plants is a more environmentally friendly alternative than chemical control (Simberloff and Stiling, 1996). Biological control also has a considerable economic advantage over chemical and mechanical controls which are 2-20 times more expensive (Cassani, 1996).

Several species of tilapia were introduced for plant control, most notably the Mozambique and redbelly tilapia (Shireman, 1984; Clugston, 1990), but these two species were of limited success. The grass carp is the primary species used to control nuisance aquatic plants in the USA. Artificial propagation made the introduction possible, as grass carp culture had been restricted to China until induced spawning techniques were developed around 1961 (Opuszynski and Shireman, 1995). Grass carp were imported in 1963 for investigation as a potential biocontrol of aquatic plants, but opposition developed immediately. The ensuing controversy epitomizes the adversarial atmosphere that can develop between proponents and opponents and interfere with rational evaluation. However, the controversy did provide impetus to investigate techniques to control unwanted reproduction. A series of symposia and workshops resulted in a proliferation of valuable literature. For a historical summary, see Stanley (1978), Shireman and Smith (1983), Shireman (1984), Cassani (1996), and Mitchell and Kelly (2006).

In the 1970s, grass carp were being cultured in eight states by more than 30 producers (Shelton and Smitherman, 1984). By 1972, diploid grass carp had been stocked in about 40 states. During the 1970s, controversy over potential natural reproduction stimulated the development of techniques to produce monosex grass carp (Shelton, 1986). Subsequently, a reputedly sterile triploid hybrid (female grass carp x male bighead carp) was introduced (Marian and Krasznai, 1978). Then, in 1982, an Arkansas fish farmer produced triploid grass carp (Mitchell and Kelly, 2006). Although the protocol used by commercial producers is proprietary, optimization of triploid induction has been reported by Cassani and Caton (1985, 1986). The various approaches to producing reproductively limited fish were significant developments in the management of fish reproduction. The direct induction of triploidy by thermal and/or pressure shock has been applied to various cold and warm water species including salmonids, catfishes, cyprinids, and cichlids (Don and Avtalion, 1988; Shelton, 1989; Donaldson, 1996).

In 1984, the USA Fish and Wildlife Service issued a biological opinion that female triploid grass carp are functionally sterile, producing essentially no viable gametes, and that triploid sperm is generally nonfunctional (Clugston and Shireman, 1987). Triploids are considered ecologically safe by most state agencies (Opuszynski and Shireman, 1995). The reproductive potential of triploids is virtually nonexistent, even under artificial induction of propagation (Allen et al., 1986; Van Eenennaam et al., 1990). The production of triploid grass carp greatly reduced the conflict in the USA over the use of grass carp. Stocking encompasses watershed ponds as well as large water bodies (>50,000 ha) with single stockings of over 400,000 triploids. Several states permit only triploids to be stocked. Therefore verification of triploidy is necessary, as some diploids are produced in direct induction and cannot be visually identified. A blood sample from each fish is tested by the producer using a coulter counter and diploids are culled. In a certification process, several fish are taken from the 3N-group and polyploidy is independently verified before shipment or at the destination (Griffin, 1991). If a single diploid is found during this certification phase, the entire load is condemned (Allen and Wattendorf, 1987).

Despite the requirement to individually test each progeny from direct 3N-production of grass carp, economically viable commercial operations have developed in the USA. Most triploid grass carp producers are in Arkansas. The direct value to fish farmers is US$2-6 million annually (Table 8). In the 1990s, about 0.5 million triploid fingerlings were stocked annually, 75% of the fish stocked since some states permit stocking diploids (USFWS, 2001).

Natural reproduction of grass carp in open surface-water systems has been documented since the 1980s by collection of fertilized eggs and larvae (Brown and Coon, 1995), confirming predictions made by Stanley et al. (1978). However, this evidence of natural spawning predated the use of triploids. Diploids were in the major river systems for nearly two decades before reproductively limited stocks were produced. Natural reproduction of escaped silver and bighead carp in the USA has also been reported since larvae were collected from various river systems (Freeze and Henderson, 1982; Schrank et al., 2001).

Other Chinese carps have been considered for water quality management in the USA and elsewhere. Silver carp and bighead carp have been investigated to manage plankton (Lachner et al., 1970; Henderson, 1978; Leventer, 1984; Milstein, 1992; Opuszynski and Shireman, 1995). Black (also called snail) carp introduction in the USA has erroneously been linked to zebra mussel control (French, 1993). In fact, the black carp was imported in the early 1980s as a biocontrol for snails in culture ponds (Venable et al., 2000). Triploid black carp stocked at 5-10/ha successfully eliminated yellow grub from a North Carolina hybrid striped bass culture (Mitchell, 1995). Researchers and commercial producers have already developed induction techniques for inducing gynogenotes and sterile triploid black carp (Rothbard and Shelton, 1993; Rothbard et al., 1997).

The black carp is the first fish species considered under the Generic Non-indigenous Aquatic Organism Risk Analysis Review Process that was authorized by the USA Congress in the Non-indigenous Aquatic Nuisance Control and Prevention Act of 1990 (NANP&CA; Nico et al., 2005). The recommendation was that black carp not be used for zebra mussel control in open waters unless research demonstrated effectiveness but use as a biocontrol of yellow grub in fish farm facilities should be allowed. The primary concern with the use of black carp in open systems in the USA is the vulnerability of endangered mollusks. Black carp have also been suggested as a potential biocontrol of snails in areas of bilharzia endemicity, but only preliminary studies have been completed (Shelton et al., 1995).

USA - Ornamentals

There are about 6,000 freshwater species in the world ornamental fish trade. Fifty-nine of the most popular are commercially reared in the USA (Conroy, 1975). Live ornamental fish trade has been increasing since the 1980s. In 1987, there were about 200 tropical fish growers in Florida with sales of about US$21 million (Clugston, 1990; USDA, 1990). Ornamental fish production is among the leading cash crops in USA aquaculture (Chapman et al., 1997). The total value of aquaculture in the USA in 1992 was over US$700 million while sales of ornamental fish in 1993 were estimated at near US$50 million. Currently, wholesale trade is estimated at US$900 million with retail trade at about US$3 billion. Ornamental fish culture is one of the most profitable aquaculture enterprises. Worldwide, it has a farm value of about US$400 million per year. More than 50% of the world's ornamental fish supply comes from Asia, with Singapore and Hong Kong being leading exporters. Israel is sixth in export value of ornamentals (FAO, 2000).

Twenty-eight species of ornamental fish have escaped and established breeding populations in Florida (Conroy, 1975; Courtenay and Stauffer, 1990), ten of which have been extirpated (Shafland, 1996). Ornamental fish culture farms are often criticized on this basis although culture of these exotics reduces exploitation of natural populations in endemic areas (Allsopp, 1997). While tropical species dominate the ornamental fish trade, many varieties of two valuable temperate species are widely cultured, i.e., the goldfish and the fancy carp or koi - the living rainbows. The estimated farm level value of goldfish (aquarium fish as well as feeders and baits) is US$10-20 million in the USA alone (Martin, 1983). Recently, backyard water gardens have become popular, increasing the demand for koi and fancy goldfish.

Israel

Without cultured exotic fishes, Israel would have a limited freshwater fish supply. Only two native fishes, the blue tilapia and the St. Peter's fish in Lake Kinneret (Sea of Galilee), have developed into significant freshwater fisheries (Ben-Tuvia et al., 1983). A total of 40 species, subspecies, or hybrids have been stocked directly into freshwater bodies or raised in commercial fishponds. Only five species succeeded in establishing populations in open systems (Golani and Mires, 2000). Of the total fish supply, about 6,000 tons comes from capture fisheries in marine and fresh waters (Lake Kinneret), about 18,000 tons (38%) comes from marine and freshwater culture, and 40,000 tons (60%) is imported (Mires, 2001).

In 1999, 15,000 tons of five groups of exotic freshwater finfish were produced in Israel (Table 5): these were common and Chinese carps (47%), tilapias (39%), rainbow trout, and hybrid striped bass (Sarig, 1997). Farmed fish are almost exclusively produced on kibbutzim. Fifty-five farms with about 3,000 ha water area had an average annual yield of 4.5 tons/ha. Foodfish production has been intensified by polyculture, improved diets, and aeration. Yield increased from about 2 tons/ha in the 1950s with carp monoculture to an average of about 5 tons/ha in the 1990s. Annual fish consumption in Israel is about 10 kg/person, totaling about 60,000 tons/year (Mires, 1995a).

Common carp was introduced from Europe in the 1930s and formed the basis of fish culture until the addition of tilapia in the 1950s. Polyculture developed by the 1960s (Tal and Ziv, 1978). Common carp yields have been stable over the past couple of decades, but tilapia production increased, coming into near equivalency in the mid-90s (Rothbard 1995; Sarig, 1983, 1996). In the mid-90s, an outbreak of a carp-specific viral disease seriously impacted culture of food fish as well as koi carp.

The blue tilapia is native to the Jordan Valley but the Nile tilapia is exotic and was introduced to produce hybrids with the native blue tilapia for monosex culture. About 60% of the cultured tilapias are hybrids between these species (Hulata, 1997). The rest are red tilapia variants of various origins, but all are monosexed by hormone sex-reversal (Rothbard et al., 1983). Additional exotic species are being tested in culture systems including the Australian red claw crayfish, silver perch, hybrid striped bass, and red drum from the USA.

The production of ornamental fish does not appear in Israeli foodfish statistics but is an economically important component of fish culture. Mag-Noy is the marketing cooperative of four kibbutzim. It exports goldfish and koi, accounting for about 30% of the European market, US$12-15 million per year. Exotic fishes compose about 95% of Israel's freshwater foodfish production. In addition, the culture of exotic ornamental fish such as koi carp, fancy goldfish, golden tench, and angelfish generate significant export trade.

Latin America and the Caribbean

Brazil is a world leader in the production and export of processed chicken and pork while fish culture previously played a minimal role in production of animal protein. Per capita consumption of aquatic products is estimated to be only 5.4 kg/year, however, inhabitants of the Amazon basin are reported to eat about 55 kg/person annually (Martinez and Pedini, 1998). Two Amazonian native species, tambaqui and pacu, are commonly farmed but consumer acceptance outside the region is affected by the intramuscular bones. In 1994, only about 30,000 tons of farmed freshwater fish were harvested in Brazil. Production rose to about 50,000 tons in 1996. Culture includes 7-10 exotic species, which make up 50-75% of the aquaculture production.

Nile tilapia accounts for about one-half of the total production in Brazil and rainbow trout contributes 2,000 tons (Lovshin and Cyrino, 1998; Lovshin, 2000). Other exotic species include largemouth bass, channel catfish, African walking catfish, and the three major Chinese carps. Aquaculture development in northeastern Brazil illustrates the value of combining exotic and transplanted species. The state of Ceara is an arid region where government agencies have constructed reservoirs for water conservation (Lovshin, 1982). Between 1911 and 1980, over 200 public and thousands of private reservoirs were constructed and stocked with fish to provide food and income for regional residents. Fish species include exotics (two species of tilapia) and transplants (five species from the Amazon, one from the Parnaiba drainage, and two from Rio Sao Francisco). Harvest from 103 of these reservoirs in 1978 was over 19,000 tons and 90% was from seven introduced (exotic and transplanted) species.

Chile and Ecuador accounted for 60% of the total South American aquaculture production in 1995 with 206,000 and 91,000 tons, respectively. In the latter part of the 1990s, Ecuador began converting shrimp ponds to tilapia production and has been supplying an increasing amount of fresh fillets to the USA. Chile was second only to Norway in the production of salmonids, with 315,000 tons and 465,000 tons, respectively (IntraFish, 2001). Total world aquaculture production of Atlantic salmon in 2000 was 860,000 tons, greater than the total from capture fisheries of 700,000 tons. Norway and Chile together produced 95,000 tons of rainbow trout in 2000, compared to only 25,000 tons produced in the USA. Chile produced about 15% of the cultured salmonids in 1995 and 30% in 2000. All the salmonids cultured in Chile are exotic with 37% rainbow trout, 35% Atlantic salmon, and 28% coho salmon (Lever 1996; Martinez and Pedini, 1998).

Tilapia is a major fish crop in many countries of the Caribbean and South and Central America. Tilapia farming began on a small scale as subsistence culture in the late 1960s but was soon commercialized (Fitzsimmons, 2000a). Production and processing technology is rapidly expanding to meet local and export demands. Many countries are able to supply only their domestic market. Mexico produced nearly 100,000 tons in the late 1990s and all was utilized within the country (Fitzsimmons, 200b). Other countries are increasingly exporting processed fillets to the USA and Europe.

Europe

Rainbow trout and common carp (transplanted species in most of Europe) together account for about one-third of the total freshwater aquaculture production in Europe (Steffens, 1997). Rainbow trout were exported from the USA in the latter half of the nineteenth century and today are cultured in over 40 countries. World production was 359,000 tons in 1995 (Tacon, 1997) and now exceeds 450,000 tons. It is the principle species cultured in the 11-member European Community, reaching 220,000 tons in 1992 or about 66% of the world production and 250,000 tons in 1994 (ECD-GF, 1995; Steffens, 1997). Another important exotic species in Europe is the Pacific cupped oyster; 150,000 tons were produced in the 1990s. The Pacific oyster was introduced to Britain from the USA in 1965 because overexploitation had depleted the native fishery. Today a commercial industry has developed around this species (Matthiessen, 1991).

Taxonomic Groups

Cyprinids. Global foodfish production is dominated by cyprinids, which include the Chinese carps, Indian carps, and common carp (Tables 4, 6). Total harvest was about 10.4 million tons in 1995 and over 15 million tons in 2000. Major producing countries are China (80%) and India (14%). Top carp species are silver (25%), grass (20%), common (17%), bighead (12%), crucian (5%), and the three Indian major carps (12%, together). Common carp was the first fish known to be domesticated and cultured for food, the first to be transported outside its native range, and the first exotic species to be introduced in the USA. It is farmed in 60-70 countries and production exceeds 10,000 tons/year in 11 of these areas (Rothbard and Yaron, 1995). Worldwide production was about 1 million tons in 1991 (Billard, 1995; Wohlfarth, 1995) and 1.8 million tons in 1995 (Tacon, 1997). Production as a food fish in the USA is low, but koi carp culture is important for the ornamental market. Utilization of Chinese carps for biological control is increasing. In particular, grass carp was widely dispersed in the 1960s for management of nuisance aquatic plants. The biomass of the tremendous numbers produced and stocked as juveniles does not appear in production statistics.

Cichlids. Tilapia culture is one of the most rapidly growing sectors of world foodfish production. Since 1984, production has grown by 12% per year (Stickney, 2001). Second only to the carps, tilapia ranked sixth in production per species in 2000, about 1.3 million tons/year, and was the third most important aquatic food product imported by the USA (Alceste, 2001). Nile tilapia is the dominant cultured species, accounting for about 70% of all tilapia production. Despite worldwide introduction, the tilapia yield is only about 5% of the total farmed fish yield, due to the tremendous harvest of carps that account for over 70% of the total (Mires, 1995b; Tacon, 1997). Tilapias are cultured worldwide in over 70 countries and are exotic in all outside the African continent (Tables 6, 7).

Aquaculture in Africa has expanded from 37,000 tons in 1984 to 189,000 tons in 1998, much of the increase has been from carps and tilapias (FAO, 2000). The natural distribution of tilapias in Africa was described by Philippart and Ruwet (1982). Transplanting tilapias on the African continent is common (Balarin and Hatton, 1979). In 1992, tilapia capture fisheries in Lake Victoria caught about 100,000 tons, much of which originated from introduced species (Engle, 1997).

Worldwide tilapia culture was 183,000 tons in 1985 (Nash, 1988), 700,000 tons in 1995, and 1.3 million tons in 2000. Almost all were produced in 70 countries where tilapias are non-native (Table 6). Nile tilapia is the most widely cultured species, with 64% of the world production. Mozambique tilapia makes up about 10% of the production (Eknath 1995; Mires, 1995b; Engle, 1997). China produces the greatest amount (157,000 tons), followed by the Philippines (63,000 tons). Much of the production in the Philippines is in pens and Nile tilapia is the primary species, essentially having replaced the Mozambique tilapia

(Hopkins and Hopkins, 1983; Guerrero, 2000). Tilapia production has overtaken culture of the native milkfish, even though contemporary culture is more intensive than that in traditional low-input brackish water systems. The numerous worldwide introductions and subsequent redistributions have resulted in several genetic bottlenecks with a loss of genotypic variability (McAndrew and Majundar, 1983; Allendorf and Ryman, 1987).

Tilapia culture is one of the most rapidly growing foodfish components in the USA and imports currently far exceed production on domestic farms (Table 7). Rapid growth of tilapia production in the latter half of the twentieth century is primarily due to management of reproduction through monosexing (Shelton et al., 1978; Rothbard et al., 1983; MacIntosh and Little, 1995; Green et al., 1997; Phelps and Popma, 2000). Farmed tilapias are almost exclusively monosexed either through hybridization, hormone-induced sex reversal, or both. Israel produced about 15 million monosex fry in 1996 (Hulata, 1997). Some concern about human consumption of steroid-treated tilapia has been raised and the Food and Drug Administration of the USA is presently regulating the use of hormone treatments. Studies have demonstrated that post-treatment tissue clearance is rapid in fry of only a few grams, and that no residue can be detected one month after termination of the steroid treatment (Johnstone et al., 1983; Goudie et al., 1986; Rothbard et al., 1990). There is no evidence that consumption of hormone-treated fish is a human health hazard (Green and Teichert-Coddington, 2000).

According to the American Tilapia Association, most tilapia products (by weight) imported by the USA in 2000 were frozen whole (23,000 tons), frozen fillets (6,000 tons, equivalent to 28,500 tons whole fish), or fresh fillets (4,000 tons, equivalent to 23,000 tons whole fish). Tilapia were grown on 24 farms in 13 states for the food market in the 1980s (Shelton and Smitherman, 1984), and California was the greatest producer. Although domestic production doubled between 1986 and 1992, only 20% of the demand was met. In 1995, 24,000 tons (80%) were imported, making tilapia the third largest imported aquatic product after salmon and shrimp (Green et al., 1997). About US$1 million worth of tilapia were imported from Honduras in 1996. In 1989, about 3,000 tons of tilapia were produced in Jamaica - all were sex-reversed monosex males (Hanley, 1991).

Salmonids. Worldwide production of salmonids is dominated by Atlantic salmon and rainbow trout (Table 6). Cultured Atlantic salmon surpassed the yield from natural fisheries. In 2000, total global production was 860,000 tons, while harvest from capture fisheries was 700,000 tons (IntraFish, 2001). Norway was the primary producer of cultured Atlantic salmon (420,000 tons), with Scotland and Chile producing 125,000 and 103,000 tons, respectively. Coho salmon and rainbow trout are also important cultured salmonids. All three species are grown in Chile and all are exotic to that country. Areas with significant production of rainbow trout are Chile, France, Italy, and Denmark, each at 40,000-50,000 tons, and the USA, Germany, Norway, Spain, Finland, and the UK, all at 16,000-25,000 tons per annum (ECD-GF, 1995; Steffens, 1997). All rainbow trout production is exotic, except in the USA, and even 35% of that is cultured outside the native range.

Conclusions

Virtually all agriculture is based on exotic cultivars and domesticated non-native animals but, among farmed fish, few are more than minimally selected and native species provide the majority of cultured stocks. Nevertheless, exotic fishes contribute about 17% to global aquaculture of food fish and domestic transplanted species add an even greater component to non-native production. Several species of considerable economic importance are grown outside their native areas. Significant yields come from Atlantic salmon and rainbow trout, common and Chinese carps, and tilapias. As capture fisheries continue to falter, culture with proven species will become increasingly important for global food security, despite constraints related to ethical and environmental issues.

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Annex - Scientific Names of Fishes Mentioned in Text

Common name	Scientific name
African walking catfish	*Clarius gariepinus*
Angelfish	*Pterophyllum* sp.
Atlantic salmon	*Salmo salar*
Bighead carp	*Hypophthalmichthys nobilis*
Black carp	*Mylopharyngodon piceus*
Blue tilapia	*Oreochromis aureus*
Brown trout	*Salmo trutta*
Buffalo fish	*Ictiobus* sp.
Catla carp	*Catla catla*
Channel catfish	*Ictalurus punctatus*
Chinook salmon	*Oncorhynchus tshawytscha*
Coho salmon	*Oncorhynchus kisutch*
Common carp, koi	*Cyprinus carpio*
Crucian carp	*Carassius carassius*
Giant prawn	*Macrobrachium rosenbergii*
Goldfish	*Carassius auratus*
Grass carp	*Ctenopharyngodon idella*
Lake trout	*Salvelinus namaycush*
Largemouth bass	*Micropterus salmoides*
Milkfish	*Chanos chanos*
Mozambique tilapia	*Oreochromis mossambicus*
Mrigal carp	*Cirrhinus mrigala*
Nile tilapia	*Oreochromis niloticus*
Pacu	*Piaractus mespotanicus*
Pacific cupped oyster	*Crassostrea gigas*
Paddlefish	*Polyodon spathula*
Rainbow trout	*Oncorhynchus mykiss*
Redbelly tilapia	*Tilapia zillii*
Red claw crayfish	*Cherax quadricarinatum*
Red drum	*Scianops ocellatum*
Roach	*Rutilus rutilus*
Rohu carp	*Labeo rohita*
St. Peter's fish	*Sarotherodon galilaeus*
Silver carp	*Hypophthalmichthys molitrix*
Silver perch	*Bidyanus bidyanus*
Palmetto hybrid bass	*Morone saxatilis* (female striped x male white bass)
Tambaqui	*Colossoma macropomum*
Tench	*Tinca tinca*
Sunshine hybrid bass	*Morone chrysops* (female white x male striped bass)
Zebra mussel	*Dreissena polymorpha*