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ENVIRONMENTAL IMPACT OF INTRODUCED ALIEN SPECIES

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Contents

Anadromous: Adjective used to characterize sea fishes that swim up rivers for spawning (e.g. salmon).

Ballast: Waterproof tanks of vessels used for transporting liquids, particularly water that permits to equilibrate the ship.

Biomanipulation: Operation based on the cascading trophic interactions theory, consisting in managing an aquatic ecosystem by modifying the abundance of the organisms at the different levels of the food web through stocking selected species (generally piscivorous fish) for a given purpose (for example to reduce eutrophication of a lake or to improve the fish yields).

Brood stock: Specimens of a species, either as eggs, juveniles or adults, from which a first or subsequent generation may be produced for possible introduction to the environment.

Cascading trophic interactions theory: This theory assumes that by increasing the biomass of piscivorous fish in an aquatic ecosystem, lower levels of the food chain will be altered through a cascading effect. This model refers to the "top-draw" regulation mechanism.

DNOCS: Departamento Nacional de Obras Contra as Sêcas (Fortaleza, Brazil).

EIFAC: European Inland Fishery Advisory Commission.

Electrophoresis: A method of separating large molecules (such as DNA fragments or proteins such as enzymes) from a mixture of similar molecules in a medium through which an electric current is passed.

Full sib: Progeny coming from both same parents.

Gene: Originally defined as the physical unit of heredity but the meaning has changed with increasing knowledge. It is probably best defined as the unit of inheritance that occupies a specific locus on a chromosome, the existence of which can be confirmed by the occurrence of different allelic forms.

Genotype: Concerns all the characters of an organism contained in its genes.

GMO: Genetically modified organism, an organism in which the genetic material has been altered anthropogenically by means of gene or cell technologies.

Half sib: Progeny coming from one common parent (mother or father).

Heterozigozity: The presence of different alleles at one or more loci on homologous chromosomes.

Hybridization: Reproduction between two different species.

ICES: International Council for the Exploration of the Sea

Introduction: Movement of species or races that are intentionally or accidentally transported and released by man into an environment outside their present range.

Introgression: Genetic modification of a native population by introduced species, as a consequence of a successful hybridization without sterility.

Mt DNA: Mitochondrial DNA consists of a small circular chromosome, which is haploid and maternally inherited.

Ne: Effective population size concerns the effective number of individuals that will contribute to the implementation of introduced or transferred or stocked population in its new environment.

PCR-based RFLP: Polymerase chain reaction -based restriction fragment length polymorphism. When PCR is combined with RFLP analysis, it is possible to screen segments of mt DNA of a large number of organisms to determine levels of genetic variability.

Phenotype: Concerns the characters that are expressed by an organism, resulting from the interaction between its genotype and the environment.

Quarantine: Confinement of introduced species in a close system designed to prevent any possibility of the release of the species or any of its disease agents or any other associated organisms into the environment.

Sex reversal: Operation consisting in reversing the phenotypic sex of an organism by using, for example, hormonal treatment during the young stages of the fish.

Stocking: Repeated injection of fish into an ecosystem from one external to it. Stocked species may either be already native to the recipient water body or may be exotic to it.

Transfer: Movement of individuals of a species or population intentionally or accidentally transported and released within their present range.

Summary

Introductions of aquatic organisms are a very old practice, although the phenomenon has only become large-scale at the end of the last century. Until 1992, a total of 291 species had been transferred to 148 countries for aquaculture purposes, for recreational fishing, for improving wild stocks, for ornamental purpose or for biological control of unwanted organisms (mosquito larvae, vegetation, phytoplankton). For several species, movement was also accidental, mostly through a transport in sea vessel ballast.

Impact of introductions concern mostly fish interactions (competition, predation, and stunting), environment (turbidity, eutrophication), and habitat alterations (disappearance of weedy sites), genetic deterioration (hybridization) of wild and introduced stocks, pathologic agents co-transfer or socioeconomic impact. When appropriately managed, these species transfers can lead to great success, as observed in Lake Kariba fisheries after *Limnothrissa miodon* introduction or in the Philippines aquaculture after tilapia transfer. But they can also produce more questionable or negative effects, like in Lake Victoria after *Lates niloticus* stocking or in many countries after brown and rainbow trout introduction through predation on native fish species.

Considering benefits of fish transfers, prohibition would be unrealistic, but on the other side, potential risks inherent to such practices are not to be underestimated. As a consequence, a code of practice has been elaborated in order to reduce the negative consequences of any desired or unexpected introduction and may lead, if appropriately managed with the active participation of the main users, to responsible fisheries and aquaculture throughout the world.

The trend is currently towards a reducing of the number of transfers, but the improvement of some technologies makes highly probable that movement of genetically modified organisms or hybrids may replace traditional fish species transfers.

1. Introduction

Large-scale introductions of exotic fish species are a relatively recent phenomenon, although in Europe introductions of some species are believed to date from Roman times, when common carps, *Cyprinus carpio*, from Eastern Europe have been cultured in ponds in Italy and in Western and Southern Greece.

However, the majority of fish introductions date from the end of the last century. Two types of fish species movements are classically recognized:

- Introduced species (includes both non-indigenous and exotic species): concern any species or race intentionally or accidentally transported and released by man into an environment outside its natural range
- Transferred or translocated species (includes transplanted species): concern any species or population intentionally or accidentally transported and released by man within its natural range

Introductions and transfers are usually carried out in a limited time frame, sufficient to establish the species in its new environment. As a general principle, an aquatic organism is regarded as introduced once it has crossed a national boundary.

Stocking usually refers to the repeated injection of fish into an ecosystem from an external one. Stocked species may either be native to the recipient water body or may be exotic but previously introduced.

Naturalization refers to the establishment in the wild of free-living, self-maintaining and self-perpetuating populations of introduced fish without any support from man.

2. Trends in Introduction

Until 1989, a total of 1673 introductions concerning 291 species and 148 countries were reported (see Table 1). For the 1990s, there is no accurate information available but easier access to efficient live fish transportation means (such as liquid oxygen and plastic bags) leads to suppose that the number of introductions or re-introductions of commercial new strains may have increased significantly.

Table 1. Number of successful introductions by geographic region recorded as of 1992.

The number of species introduced into each country ranges from 79 into the USA to only one in 29 countries. Most introductions (36%) were made for aquaculture purpose, about 12% for recreational fisheries and 11% to improve wild stocks. Twenty-eight percent of introductions were either accidental through escape from aquaculture ponds and aquaria, or for reasons that are unknown.

The number of introductions indicates that the insertion of new species into native fish communities has been viewed as a legitimate management tool in the past and it will probably continue to be regarded so in the future. There is, however, strong international pressure to regulate the movement of species in order to reduce the risks of diseases co-introduction, of damage to the environment, to the native fish stocks and to the genetic composition of resident and introduced fish.

At the species level, a slowing in the number of new introductions has been detected, possibly because most practical introductions have already been made. However, given the new awareness to local genetic diversity and the current efforts to domestication, to selective breeding and to genetic engineering in favor of obtaining better varieties for aquaculture, it is probable that a future wave of introductions will take place at the level of strains, varieties, hybrids, and GMOs of already existing species.

3. Reasons for Introduction

The purposes for which species have been introduced are various. Moreover, the motives for which exotic fish species have been moved from country to country have changed with time, as shown in Table 2.

Table 2. Changes in purpose of introductions expressed as percentage within each decade for each major category of use.

Introductions made for aquaculture purposes have been the most numerous. They have always comprised a significant proportion of the total but have grown in importance in the last decades. Since the beginning of the 1970s, introductions made for this purpose have accounted for well over half of the total.

Sport fishing has provided the second major motive for introduction with a relatively constant number of introductions per decade, although introductions for this purpose have relatively declined in importance since the 1950s.

Introductions made for improvement of capture fisheries in lakes, reservoirs and rivers increased in number from 1950 to 1980, when they overtook sport fishing as the second most important reason.

The use of fish species to control unwanted organisms has a long history but most of the introductions made for this purpose have been concentrated in the decades from 1950 to 1980.

Three categories of introductions are more problematic. Private operators have made most of the introductions of fish species for ornament and some have resulted from escapes into the wild. Dates of introductions are generally unknown and trends are difficult to assess. The dates of introductions due to various types of accidents are also generally unknown and introductions made for motives, which are unknown, declined since the 1940s. The most substantial reduction in this category since 1970 indicates that introductions of exotic species have been more carefully documented in recent years.

3.1 Aquaculture

Exotic species have played an important part in the development of aquaculture. As a result of this trend, only nine species accounted for 78% of the total world freshwater fish-culture in 1996. These major species for fish-culture have been introduced into countries throughout the world.

As of 1988, 98 species of fish have formed the subject of international introductions associated with aquaculture. Early international movements of species, up to 1900, mainly involved freshwater salmonids such as *Oncorhynchus mykiss* and *Salmo trutta trutta* which were introduced into temperate regions for aquaculture associated with the maintenance of sport fisheries, as well as for limited food production. Since the 1970s, salmonids introductions (mainly *Salmo salar* and

Oncorhynchus kisutch) have involved anadromous forms, which are being used dramatically increasingly for mariculture in cages (Norway, Chile).

Common carp reached its maximum level of introduction and transfer in the decades between 1920 and 1940 and was then successively replaced by tilapias (1950–1980) and Chinese carps (1960–1980) as preferred species. Current trends point to an increasing number of crustacean species, which are being introduced worldwide for the rapidly expending brackish water shrimp culture.

The failure to deploy what are often judged equally desirable local species for aquaculture has often been cited as a criticism for this policy. However, there is a well-known trend for food producers to cut risk by using culture technologies that are already established. This explains the relatively narrow selection of species used in contemporary aquaculture. But there is now a tendency towards exploring the potential of "new" local species, mainly in tropical continents: South America, Africa and South East Asia.

3.2 Management of Inland Waters

The second category of introductions refers to those aiming at the manipulation of wild, or modified stocks in natural water bodies. Stocks of this kind are used for sport or recreational fishing and for a variety of food fisheries ranging from subsistence to fully commercial.

3.2.1 Recreational Fishing

As of 1988, seventy-eight species were recorded as having been introduced for sport purposes. A great number of these are salmonids or larger predators having the fighting qualities sought by sport fishermen. The earlier decades of the century were mainly concerned with salmonids transfers whereas later, centrarchid species (large mouth bass, *Micropterus salmoides* and pikeperch, *Stizostedion lucioperca*) were introduced into a wide number of countries.

Many introductions made originally for sport fisheries have subsequently been adopted for aquaculture or have formed stocks, which are now exploited by subsistence or commercial fishermen.

3.2.2 Improvement of Wild Stocks

The motives for introducing fish species in order to improve wild stocks are numerous: establishment of new food fisheries, filling "vacant niches," stocking natural waters, providing forage for predators, restoration of fisheries, establishment of a wild stock, control of stunted species... This applies particularly in faunistically impoverished regions such as temperate zones, which suffered glaciation during the Ice Age, islands east of Wallace's line or high elevation mountain waters. For the same reason, introductions have often been made to man-made lakes in which autochthonous species have been unable to establish themselves. In fact all the fish introductions for improving wild stocks refer more or less to the concept of "vacant niche" in the sense that there are resources within a water body which are not being used efficiently due to lack of suitable indigenous species.

The introduction of one species has often resulted in the need to follow it with another. When piscivorous fish species, for example, are introduced into fish communities, which have not evolved in the presence of such predators, the consequential decline or extinction of indigenous species has frequently rendered the introduction of replacement prey fishes essential. Classic examples of this situation are the introductions of *Lepomis* spp. to counterbalance the effects of black bass introductions, or the use of tilapias or *Cichlasoma* spp. as forage for *Cichla ocellaris*. Another example of this type of successive introductions occurs when herbivorous fish such as grass carp or common carp exert a eutrophicating effect on the water by converting primary producers from macrophytic to phytoplanktonic organisms. The resulting algal blooms can reach nuisance proportions and the phytoplanktivorous silver carp *Hypophthalmichthys molitrix* has often been introduced to curb excessive growths of blooms. This kind of fish associations refers to fish farming polyculture practices and can be extended to small water bodies' management for extensive fish culture.

Several successes have followed the introduction of species as a foundation for capture fisheries, although negative effects may also happen (see: impacts of introduced fishes).

3.3 Example of Africa

Tilapiines, a native African fish Tribe within the family Cichlidae, have proved to be highly successful colonizing species in many countries due mainly to a suite of intrinsic biological attributes, including their rapid growth rates, wide physiological tolerances and habitat preferences, and their ability to feed on different components of the aquatic food chains so that they can exploit unutilized food resources in many systems. They also have a highly efficient reproductive strategy involving the mouth brooding of new recruits for *Oreochromis* and *Sarotherodon* species.

In African natural waters and man-made impoundments, introductions of tilapiines, generally together with fish species from other families, occurred for several reasons:

- Stocking natural lakes where no fish at all was present like Lake Nakuru (Kenya) and where *Oreochromis alcalinus grahami* was introduced, or where no tilapias were present like Lake Naivasha (Kenya) where *Tilapia zillii*, *Oreochromis spilurus niger* and *O. leucostictus* were introduced
- Filling a supposed vacant ecological niche in natural or man-made lakes. In Lake Kyoga (Uganda), the introduction of *Oreochromis niloticus* in the 1950s together with *Lates niloticus* allowed commercial fisheries to develop. Before the introduction of these fish species, the total fish landing was low (4500 t) and the native species constituted the bulk of the catch. In 1977, the commercial catch rose to a peak of 167 000 t where *Oreochromis niloticus* and *Lates niloticus* accounted for 41% and 42% respectively. At the same time, the native tilapiines disappeared from the reported commercial fisheries (which does not mean that they disappeared from the lake). In Lake Victoria, the introduction of the same two species allowed the total landings to reach more than 500 000 t in 1990 from 100 000 t during the 1970s, with a contribution of 300 000 t and 60–70 000 t from *L. niloticus* and *O. niloticus* respectively. In Cote d'Ivoire, it was estimated in 1988 that two introduced species, the tilapiine *Oreochromis niloticus* and the osteoglossid *Heterotis niloticus* accounted both for 50–70% of the total catch from inland fisheries. In the two major man-made lakes of this country, Lake Kossou and Lake Buyo where several tilapias species of genus *Tilapia* and *Sarotherodon* were already present, the introduced *Oreochromis niloticus* allowed the contribution of tilapias to total landings to increase from 50% to 80% in Lake Kossou from 1974 to 1987 and from 21% to 64% in Lake Buyo from 1980 to 1988. In Lake Buyo, *Heterotis niloticus* introduced in 1980 accounted for 16% of total catches eight years later. The aim of these introductions, which was to promote artisanal fisheries can be considered as successful operations

The success of the Lake Tanganyika fishery, based largely on catches of pelagic clupeids (*Limnothrissa miodon* and *Stolothrissa tanganicae*) which feed on the abundant plankton, gave rise to proposals for the introduction of these clupeids into other lakes lacking pelagic fish species. In 1967 and 1968, *Limnothrissa miodon* was introduced into the man-made Lake Kariba where it allowed a sustainable fishery to develop. The colonization of Cabora Bassa reservoir, below Lake Kariba downstream the Zambezi River was even possible by individuals of *L. miodon* surviving passage through the hydroelectric turbines. In Lake Kariba, the total annual fish production from fisheries was estimated to be 2 600 t in 1970, twelve years after impoundment. First catches of

Limnothrissa miodon were recorded in 1974 (500 t) and in 1991, total catches from the Lake were estimated at 30 000 t of which 26 000 t were *L. miodon* allowing the development of a sustainable commercial fishery.

The two species of Lake Tanganyika clupeids were also transplanted into Lake Kivu between 1958 and 1960 and an artisanal fishery started to exploit the clupeid stock at the beginning of 1980s. This plankton feeder occupied a vacant niche and the stock gradually developed and increased in size. This introduction has been presented as a biological and economical success and at the beginning of 1990s amounted to nearly two-thirds of the total catch.

3.4 Example of Asia

Exotic fish introductions into Indian freshwaters are illustrative of what has happened throughout Asia. The list of species movements includes the intra-Indian transfer of major carps, the sport fishes and in addition, the European carps, *Cyprinus carpio*, *Carassius carassius* and *Tinca tinca*. All these temperate species were moved to tropical regions. Tropical intra-Indian transfers included the piscivorous *Ophiocephalus* and the herbivorous estuarine cichlid *Etroplus suratensis*; others included *Osphronemus goramy* from Indonesia and *Oreochromis mossambicus* from Africa. In Sri Lanka, 19 introduced fish species were recorded (excluding larvivores and ornamentals).

From various studies carried out throughout Asia, the summarized assessment of the impacts of fishes introduced is that they have entailed few losses of native species. There was a note though of caution against complacency about fish introduction and a plea for regulation. In sharp contrast to this assessment is the loss of 38 of Singapore’s 70 freshwater fishes: presumably, this loss is a result of urbanization.

Considering the group of extra-tropical carps including Indian, Chinese and common carps introduced widely in tropical Asia, their impact on fish yields has not been negligible but they are costly to cultivate and their use for improving inland fisheries in the tropics is diminishing. They have the advantage of not breeding naturally in tropical waters but they are uneconomic. In Sri Lanka, *Cyprinus carpio* has been stocked in reservoirs for 45 years with no economic return, while in Southern Indian reservoirs there is a negative regression between common carp and total fish yield. In Sri Lanka, the establishment of culture-based fisheries in perennial reservoirs using non-tropical major carps is irrational, because it appears that the optimal yield that can be achieved from this practice is about 30 $kg.ha^{-1}.year^{-1}$ when normal fishing using gillnets is carried out, by contrast to 300 $kg.ha^{-1}.year^{-1}$ for tilapias. Moreover, this practice will have to be implemented at the expense of the existing productive tilapia fishery, and it will lead to overexploitation fishery as a result of the use of efficient fishing gear. Also major carps have to be hatchery-reared and raised to fingerling size, in contrast to the cichlids which have established natural breeding populations.

In Thailand, exotic carps and *Oreochromis niloticus* have been stocked into reservoirs, the former at a considerable cost as only *O. niloticus* has contributed significantly to the reservoir fish catch while no positive economic return from exotic carp stocking was demonstrated. In 1986, 23 000 tons of *Oreochromis* were harvested while only 4000 tons of stocked common carp were caught from the reservoirs (no other exotic carps were reported). Thus, it appears that attempts to use them to stock lakes and reservoirs have not been successful economically.

In Sri Lanka, fish yields of all carp species, including Indian, Chinese and common carps, also show negative curvilinear relationships with the reservoir area. Similar relationships between reservoir area and yield of stocked fish have been found in China, India and Cuba. High fish yields through stocking can only be achieved in small (< 800 ha) reservoirs. This is probably because the number of fingerlings needed to ensure high recovery rates in larger reservoirs is too high. Since the cichlid fish yields in the capture fisheries from perennial reservoirs fisheries are positively correlated with the reservoir area, establishment of the culture-based fisheries for carps is reasonable only in small reservoirs where cichlid yields are low. Furthermore, establishment of culture-based fisheries in small perennial reservoirs where high recovery rates can be ensured by using efficient fishing methods should go together with community-based management of the fisheries.

A second group of exotics including tropical species such as the gourami's, carps and cichlids can be considered. None of these former have so far had a major impact on either capture or culture-based fisheries. In contrast, the tilapias from Africa have been widely dispersed since the 1950s and the impacts of their introduction on both capture and culture fisheries in tropical Asia have been spectacular. Sri Lanka, which had no noteworthy inland fishery, now harvests 25 000–30 000 tons of tilapia from reservoirs representing 300 $kg.ha^{-1}.year^{-1}$ as a mean value for about 100 000 ha of large shallow reservoirs. This situation is best exemplified by the dramatic increase in fish production in Parakrama Samudra reservoir, from less than 10 $kg.ha^{-1}.year^{-1}$ prior to the introduction of *O mossambicus* in 1952 to 180 $kg.ha^{-1}.year^{-1}$ in 1967 and 450-500 $kg.ha^{-1}.year^{-1}$ in 1975–1980. Tilapias (*O. mossambicus, Tilapia rendalli* stocked in 1972 and *O. niloticus* stocked in 1982) accounted for more than 50% in total catch and up to 90% certain years, with no negative impact on indigenous species.

In tropical India where tilapias are not considered desirable, reservoir management includes regular stocking with extra-tropical carps. The fish yields are about 20 $kg.ha^{-1}.year^{-1}$ but when present, tilapias enhance fish yields while common carp seems to depress yields. In Indonesian Jatiluhur reservoir, tilapias dominate the catch and have a positive impact on yields although the fish yield is only 15 $kg.ha^{-1}.year^{-1}$ due to deepness and turbidity that reduces primary production.

Tilapias have had a remarkable impact on tropical Asian capture fisheries raising yields from 20–40 $kg.ha^{-1}.year^{-1}$ with indigenous species in shallow reservoirs to more than 10 times that figure under favorable conditions.

3.5 Example of America

In tropical America, the same pattern of fish introductions has occurred as in the Asian tropics. However, there are differences in the timing and the species used. Tropical South America has a rich indigenous riverine fauna whereas Central America on the other hand has a very limited fauna of freshwater fishes. Fish introductions came to tropical America later than to Asia. The earliest introductions were of sport fishes followed by extra-tropical carps for culture and the intra-American transfer of species. The impact of piscivorous fishes, which was well documented for Cuba and Mexico and showed a negative impact on indigenous fish, can be considered as a general rule for tropical America. This is in sharp contrast to Asia where herbivores and omnivores comprise the majority of introduced species. For Northeast Brazil, a well-documented account of both the sequence of fish introduction and the changes in the reservoirs fisheries is available. Local, Amazonian and exotic species of fish were introduced and the fish yields in reservoirs are substantial. Tilapias contribute about 30% of the catch in DNOCS reservoirs.

Figure 1. Evolution of fish landings in 103 Northeast Brazil reservoirs following the introduction of two tilapias species (after Fernando, 1991, modified).

In Mexico, the inland fish catch, which comes mainly from reservoirs, consisted of 65–72% of tilapias in 1982–1985. In Lake Chapala, the largest natural lake in Mexico, 70% of the 26 $kg.ha^{-1}.year^{-1}$ catch consists of tilapias. The same pattern can be observed in the Dominican Republic. In some Cuban lakes, the indigenous fishes, or what was left of them after decimation by bass, had a low production compared with introduced bass and sunfish. In Cuba, the mean annual catch of tilapias for 1970–1974 which was 14 tons, reached 10 000 tons for 1980–1984 and accounted for 93% of the total catch of all species from inland waters of the country.

In tropical America, just like in Asia, piscivorous fishes have caused a negative impact on indigenous fishes but the role of exotic sport fishes and extra-tropical herbivores, and omnivores remain altogether negligible. Tilapias, on the other hand, have made substantial introductions to the fisheries and apparently have caused no harm to indigenous fishes.

3.6 Ornamental

Fishes introduced for ornamental reasons can be divided into two groups. First, large species introduced for stocking into natural waters or ornamental ponds: the main species used for this purpose is the goldfish *Carassius auratus* which has been widely distributed outside its natural range and which has frequently escaped into the wild.

The second group consists of the innumerable species of small, mostly tropical fish, which have been widely dispersed by the flourishing aquarium trade. While the majority of these species are unable to survive under normal conditions in temperate climates, some have been able to establish temporary breeding populations in artificially heated effluent water or in natural thermal springs.

In tropical climates, for example Brazil, Colombia, Malaysia, Peru, Singapore, Thailand, and Florida, the situation is much more serious. Escapes from tropical aquarium fish farms in the host countries have been frequent and are almost certainly the main source of naturalized populations in these and in other countries.

3.7 Biological Control

3.7.1 Unwanted Aquatic Organisms

Early attempts in the 1920s in the use of exotic fish species to control unwanted aquatic organisms were concerned principally with the attempted eradication of mosquito larvae. Twelve species have been introduced for mosquito control, but most extensive introductions have been made with 3 species: *Poecilia latipinna*, *Poecilia reticulata,* and *Gambusia affinis*.

Control of mosquito larvae by these small larvivorous fish species is highly effective and is replacing the more costly and environmentally harmful control with insecticides. The introduced *Gambusia* sp. is now gradually being replaced by native larvivorous species.

The introduction of molluskivorous fishes has been proposed for controlling the aquatic snail vector of *Schistosomiasis* (bilharzia). Despite the existence of numerous apparently suitable fish species, control in larger water bodies appears to be ineffective. For more limited aquatic environments and in fishponds, the cichlid *Astatoreochromis alluaudi* is reported to reduce by at least more than 50% the snail populations. Other fish species, such as *Mylopharyngodon piceus* and more recently *Heterotis niloticus* have been reported to feed widely on gastropods.

3.7.2 Aquatic Vegetation

Numerous species of fish are reported to feed on aquatic weeds but, up to now, only a very small variety of species has been introduced specifically to control aquatic vegetation. The grass carp, *Ctenopharyngodon idella*, has been, by far, the most introduced and utilized species for this purpose and far behind species such as *Tilapia rendalli*, *T. Zillii* and *Oreochromis mossambicus* which is however definitively not a macrophytophage.

Grass carp has been successfully used for controlling aquatic macrophytes in many countries and probably provides the only practical method when the use of herbicides is too costly or undesirable. This species normally has the advantage that it does not breed naturally in the waters to which it is introduced thus permitting periodic adjustments in the number and sizes in fish present. It is also considered a valuable edible species in many areas of the world and can play a useful secondary role in food supply.

3.7.3 Blooms of Phytoplankton

Silver carp, *Hypophthalmichthys molitrix* has been introduced to many countries with the purpose of controlling heavy algal blooms in natural waters and man-made lakes with a high rate of success.

3.8 Accident

Exotic fishes have become accidentally naturalized outside their natural range by escaping from captivity, natural diffusion, accidental transportation with other species and, more rarely, as stowaways in the ballast-water tanks of trans-oceanic vessels.

Once established in one place or in one country, some species have diffused through freshwater systems to other places or to other countries. Examples in this category include the giant gourami, *Osphronemus goramy*, which escaped from fish farms in Madagascar; common carp introduced to Brazil which spread from the Uruguay River into Uruguay and Argentina; *Limnothrissa miodon* which escaped from Lake Kariba downstream the Zambezi river to establish itself in Lake Cabora Bassa in Mozambique. In Zimbabwe, *Oreochromis niloticus* appeared since 1989 in the fish catches from Lake Kariba following its escape from fish cages implemented on the lake. The impact of this accidental stocking is difficult to predict: probably minor on the important clupeid *Limnothrissa miodon* which occupies a different ecological niche, but probably major on native tilapia species, *Tilapia rendalli* and *Oreochromis mortimeri,* which have similar diets based mainly on phytoplankton, but also on decayed macrophytes, detritus and some zooplankton, and insect larvae.

4. Impact of Introductions

Although, the temporal scale is an important factor to be considered in evaluating impacts of species transfers, it seems that for many species, introduction did not entail a visible negative impact. But more generally, it is considered that these operations may have consequences in regard to fish interactions, environment and habitat modifications, genetic deterioration, new diseases introduction and socioeconomic context.

4.1 Fish Interactions

Considering the direct interactions between introduced and native species, introduced organisms can alter trophic relationships in at least three different ways. First, their presence may significantly increase the amount of prey available to native predators. It is the case in Lake Kootenay (Canada) where introduction of shrimp *Mysis relicta* entailed a change in the feeding regime of *Oncorhynchus nerka,* which, as a consequence of its shrimp consumption, proliferated more quickly than *Oncorhynchus mykiss,* which did not benefit of this introduction.

Second, the feeding habits of introduced fish can reduce the amount of natural feed available to native species through a dietary overlap (competition). Competition is not limited to trophic interactions but includes also such other ecological limiting factors as breeding space. For example, in Russia, a number of fishes, which were accidentally introduced together with *Ctenopharyngodon idella,* resulted in declines in local species with same feeding regime through superior growth and fecundity. Similar mechanisms have been recorded with native species unable to compete with introduced tilapiines in some Southern States in the USA; with *Parachromis managuensis* which displaced local predators in El Salvador; with *Poecilia reticulata,* which induced the decline in numbers of local cyprinodonts in Uganda and in Southwestern USA; and *Lepomis auritus,* which has supplanted *Alburnus alburnus* in some Italian oligotrophic lakes.

In Lake Victoria, the introduced *Oreochromis niloticus* and *Tilapia zillii* have become important in the fishery but this at the expense of the indigenous tilapias *O. esculentus* and *O. variabilis* by sharing the same nursery habitats to the detriment of the autochthonous species. Similarly, in Lake Kossou (Côte d'Ivoire), introduced *Oreochromis niloticus* became dominant in the catches but did not eliminate autochthonous tilapias, *Tilapia zillii* and *Sarotherodon galilaeus galilaeus*, which accounted still for about 25% of total tilapias landings. This situation is explained by the fact that *O. niloticus* through its opportunistic feeding habit, its fast growth, its reproductive efficiency and its aggressive behavior is able to dominate other species occupying the same ecological niche. Aggressive behavior from introduced brown trout has altered distributions patterns of indigenous salmonids in the United States of America. In Lake Luhondo (Rwanda), the introduction of *O. niloticus* has caused the decline of two native cyprinids, *Barbus neumayeri,* and *Varicorhinus ruandae,* which survived only in some small tributaries of the lake or in the nearby inflowing rivers and the disappearance of the large barbel *Barbus microbarbis*.

Sometimes, competition can occur between introduced species, and in this case, it is possible that only the best-adapted species remains in its new environment.

The third type of fish interaction is predation, as introduced carnivorous fishes can deeply affect the population dynamics of indigenous prey species. The best-known example is the introduction and spread of *Lates niloticus* in Lake Victoria. This predatory fish has possibly led to the extinction of over 300 species of haplochromine cichlids and is considered by many as a major ecological disaster.

Nevertheless, some other factors have been proved to have played a major rule in the decline of native species such as the impact of human activities in the vicinity of the lake and major changes in the limnological characteristics of the lake over the last 30 years (increase in algal biomass and in primary production, and dramatic decline in hypolimnetic oxygen with anoxia below 40 m seasonally).

Eutrophication as well as the introduction of new fishing techniques (trawling) contributed to the decline of the haplochromine fauna, which was, moreover, already affected by over fishing before the establishment of *Lates niloticus*. In this case, the detritivore/planktivore group of haplochromines, as well as the zooplankton group, which constituted 40% and 16% respectively of the total demersal fish biomass disappeared in the 1980s simultaneously with the explosive increase of the introduced *L. niloticus*. They have been replaced by the native detritivorous atyid prawn *Caridina nilotica* and the native zooplanktivore cyprinid *Rastrineobola argentea* which both became the major prey for the Nile perch. Whereas the haplochromines converted numerous protein sources (algae, zooplankton, insect larvae, and mollusks, etc) into fish protein for consumption by higher levels, Nile perch now eats considerable amounts of its own juveniles, which in some way feed on the same food items as the haplochromines did previously.

Another example could be that of *Cichla ocellaris* in Gatun Lake in Panama, although the supposed eliminated species later recolonized the lake from refugia. In Lake Titicaca, *Odontesthes bonariensis* and *Oncorhynchus mykiss* were implicated in the decline of stocks of native *Orestias* and *Trichomycterus* species. Rainbow trout *Oncorhynchus mykiss* was also implicated in the decline of Andean *Orestias* sp. and *Trichomycterus* sp. in Colombia and Chile, of native salmonids in Lake Ohrid (Yugoslavia), of *Schizothorax* sp. in Himalayan rivers, of *Pseudobarbus quathlambae* in Lesotho, of *Sandelia capensis* in South Africa, of *Protoctes oxyrhynchus* and *Galaxias gracilis* in New Zealand and other galaxiids in Australia. Other predators that have been blamed for the disappearance of local species are *Micropterus salmoides* and brown trout *Salmo trutta fario*. Feeding by large carnivorous species on adult prey is not the only type of predatory interaction. Many smaller species can prey on juvenile fishes and some cyprinodonts, particularly *Gambusia affinis*, or *Lepomis gibbosus* are reported to feed on the eggs of other species.

The quality of the fish stock can also deteriorate through stunting by the introduced species. Stunting is a process whereby the population of a species expands rapidly, producing large numbers of individuals which mature and breed at a much reduced size, thus diminishing considerably its recreational or commercial value. Fish species, which have been reported as producing stunted population, include *Alburnus alburnus*, *Carassius auratus*, *Lepomis cyanellus*, *L. gibbosus*, *L. macrochirus*, *Oreochromis mossambicus*, *O. niloticus*, *Tilapia rendalli* and *Perca fluviatilis*. Stunted populations can overwhelm existing ones and may even in extreme cases cause a shortage of oxygen.

The reduction in the population size of an autochthonous species can also occur, and it is difficult to attribute it with certainty to predation or competition from an exotic fish species. On occasion both influences may act in concert. Salmonids, especially brown and rainbow trout have, partly because of their exceptionally wide naturalized distribution, one of the worst records for damaging native fish species.

4.2 Environment Alterations

Compared with direct effects of predation and competition, the effects on environment by naturalized introduced fishes may be subtler. Their consequences can have repercussions on several trophic levels. Aquatic food webs are very complex, particularly in tropical areas, and some attempts were made to modernize their functioning, in order to be able to predict consequences of an exotic fish introduction. The best known is the cascading trophic interactions model (and subsequent work), which postulates that the biomass of a population is the result of equilibrium between available trophic resources (bottom-up control) and predation exerted (top-down control). So, considering a classical food chain, a rise in piscivore biomass results in decreased fish zooplanktivore biomass, which in turn allows an increase in large herbivore zooplankton biomass, and decreased phytoplankton biomass. The opposite scheme can also be considered, as an increase in planktonic algae might influence carnivorous species through the trophic cascading interactions. This theory gave good results when applied to North American and North European lakes. It allowed linking several trophic levels and as a consequence, sustained the idea of introducing predatory fishes to fight lake eutrophication. This management has been called biomanipulation, and it consists in introducing a predatory fish, which, through the cascading trophic interactions, entails a decline in phytoplankton abundance through the elimination of zooplanktivore fish in order to allow the increase of phytoplankton grazing by herbivore zooplankton. Biomanipulations can also be used to manage the aquatic food web in order to improve the fishery production. But, biomanipulations sometimes produced results that were as undesirable, or even more, than the micro-algae proliferations that were to be controlled. As a matter of fact, phytoplankton decline increases water transparency, which in turn can entail macrophytes (*Elodea* sp., *Potamogeton* sp.) and periphyton (*Cladophora* sp.) proliferations.

However, cascading trophic interactions models are not very useful for warm temperate and tropical lakes where food chains are not linear, so that predicting the consequences of a fish introduction is very difficult. In Lake Victoria, cascading trophic interactions would have predicted that introduction of Nile perch should have led to lower phytoplankton densities, whereas the opposite has been observed. If one does not consider other potential impact such as pollution, disruption and reduction of the diverse and trophically complex haplochromine community may have initiated changes in food web structure and nutrient cycling that resulted in eutrophication. Moreover, consequences can be much larger than the modification of the sole aquatic ecosystem.

For example, another consequence of the introduction of *Lates niloticus* into Lake Victoria, and the subsequent crash of the native cichlid populations feeding on invertebrates, was a population explosion of emergent insects, which at times resembled a cloud over the lake. This insect proliferation in turn now supports a huge population of the sand martin *Riparia riparia*. Other changes were also observed, as the shift of the pied kingfisher's diet (*Ceryle rudis*) from a feeding based on haplochromines to a less energetically interesting food consumption based on *Rastrineobola argentea*. Similar shift in diet was also found for the great cormorant (*Phalacrocorax carbo*) and the long-tailed cormorant (*Phalacrocorax africanus*). Another example could be *Cichla ocellaris* introduced in Panama, which did not only eradicate seven native fish species, but also entailed the disappearance of piscivorous birds and a sudden resurgence of human malaria as a consequence of the predation on the small fish that used to feed on mosquito larvae.

Finally, behavior of some species is very unpredictable, as some fish may adopt a niche that differs completely from that occupied in their native range. The most striking example of such behavior is given by *Oreochromis mossambicus*. This species is adapted to moderate salinity as it inhabits estuaries in its normal habitat, but it also penetrates marine atoll in Micronesia, which was unexpected. Similar flexibility has also enabled other cichlids to expand outside of temperature ranges that would normally be limiting such as in the Southern United States where species (*Oreochromis niloticus*, *O. aureus* and hybrids) that are normally tropical have established themselves in sub-tropical or even warm temperate regimes.

4.3 Habitat Alteration

The consumption of plant material by herbivorous fishes, the uprooting of macrophytes through digging for food or for nesting sites and the organic enrichment which increases turbidity and thus reduces light penetration and photosynthesis can involve the displacement of aquatic vegetation. The common carp *Cyprinus carpio*, through its habit of rooting around in the bottom, has the reputation of muddying the waters it occupies. This shades out macrophytes, cokes benthic invertebrates and through the more rapid recycling of phosphate contributes to accelerated eutrophication. As a result, the composition and abundance of the native fish fauna is altered, as in India where species of the genus *Schizothorax* have disappeared from waters to which carp had been introduced, together with the fisheries based on them.

Ctenopharyngodon idella has been introduced into many areas of the world with the intention of eliminating submersed and emergent vegetation. It usually performs this task adequately but, through selective feeding on more tender (soft leaved) species may favor the development of tougher vegetation, which is even more of a nuisance. In Eastern Europe, it was observed that in both natural and man-made lakes, and in large channels stocked with grass carp, the species composition of both macrophytes and phytoplankton changed dramatically, and the total catch of fish declined significantly, particularly for those species whose reproduction invariably needs aquatic plants. The removal of submersed vegetation, in which phytophilous fishes spawn, may inhibit their breeding. It also affects native fishes and other animals, as plant provide a variety of facilities, such as oxygen, substrate and nutrient for invertebrate species, cover for early stages of fishes and feeding places for water birds and aquatic mammals. Concern has also been expressed over the elimination of benthic weeds with consequences such as substrate alteration and turbidity increase through wave-mediated erosion and the continual mixing of silt previously stabilized by the roots of aquatic vegetation.

Other examples of modifications to the habitat are produced by burrowing forms of crustacean *Procambarus clarkii* and *Eriocheir sinensis*, both of which are judged pests due to their habit of constructing galleries in levees and pond banks.

Interactions between native and introduced fishes may be of significance to the distribution, density and existence of the former. Interference competition arising from aggression and territoriality may cause indigenous stocks to be displaced from favored microhabitats such as feeding grounds, nesting sites and to remain only in refuge areas. These refuges may play a significant role in later recolonization, as seen in Panama where the species supposedly eliminated by *Cichla ocellaris* later recolonized the lake from such protected places.

4.4 Genetic Deterioration

Release of fish into the wild can have genetic impacts at three levels: on the individuals released, on specific native individuals or on closely related indigenous species, and the effects can be either direct or indirect. Direct impacts include those that operate on a species by initiating changes in gene flow, through hybridization and introgression. Indirect effects are primarily those caused by inadequate number of spawners, either through release of a small number of individuals, or in the indigenous species through ecological processes such as competition, predation, new diseases or parasites. Such genetic effects may lead to a loss of locally adapted populations and genetic diversity.

The evolutionary outcome of the direct effects may depend critically on whether the released fish are taken from the wild or from cultured stock.

Domestication, which involves changes in the quantity, variety or combination of alleles, produces effects similar to the loss of within-population diversity in nature, except that in nature the loss of diversity by genetic drift is random in character whereas diversity lost due to domestication is related directly to specific characters. Moreover, the effect of drift on genetic diversity is inversely proportional to effective population size, whereas through domestication, genetic diversity is lost in relation to the genetic nature of the trait and selection intensity. For that reason, if domestication allows improvement in culture, it can also entail a decrease in performances in the wild, as domesticated fish frequently show weaker results than wild ones, in regard to the survival of fingerlings and adults, concealment behavior, swimming stamina, straying and return rates, and susceptibility to diseases.

Since phenotypic and genetic characters may shift during captivity, interbreeding with native populations or species may lead to a dilution of locally adapted gene pools, and reduction in native population performance through loss of species characteristics.

Fishes have a greater potential for successful hybridization without sterility than either mammals or birds, and this may lead to complex introgression when domesticated fishes meet the wild stocks. Exotics may thus interbreed with either native congeners or with other aliens.

Under the pressures exerted through introduction, normal behavior patterns may be abandoned and hybrids arise from species or genera that do not normally interbreed. For example, in Sri Lanka, the proportion of *Oreochromis niloticus* has increased following heavy stocking of some reservoirs since its introduction into this country in the mid-1970s and introgressive hybridization with *Oreochromis mossambicus*, introduced in 1952, has taken place in most reservoir populations. Moreover, it was hypothesized that hybridization may lead to an imbalance in sex ratio and reduced fecundity in reservoir populations of cichlids in the long term, resulting in low yields in the fisheries. In Lake Naivasha (Kenya), *Oreochromis spilurus* introduced into the lake in 1925 was abundant in the 1950s and 1960s but hybridized with *O. leucostictus* following its introduction in 1956. Both *O. spirulus* and the hybrids have since disappeared from the lake, *O. leucostictus* being the only remaining from the three populations. Similar hybridization occurred in Lake Itasy, Madagascar, between two species of Oreochromis: *O. macrochir* (long fin tilapia) introduced to the lake in 1958 and *O. niloticus* introduced in 1961. The hybrid, known locally as “tilapia trois quarts” appeared in the commercial catches in 1965, at the same time at which *O. macrochir*, which constituted the bulk of the fishery in the early 1960s, started decreasing. Subsequently, Nile tilapia established equilibrium with the new hybrid (55% and 40% of the total catch from the lake respectively during the 1980s) while long fin tilapia has virtually disappeared. The much higher fecundity of the hybrid compared to that of *O. macrochir* at the same size has been proposed as an explanation of this situation.

In Africa and Latin America, there has been a widespread breeding of different genetic strains, particularly of the tilapiine cichlids, which has already resulted in a considerable mixing of the gene pool.

Indirect effects arise from the impact of reductions in population size on genetic diversity, either through release of too few individuals (founder effect), high mortality due to adaptation to new environments (population bottleneck) or ecological effects on native fish through such forces as competition, predation or transfer of diseases or parasites from introduced fish. The latter effect is being considered in the next paragraph.

In order to minimize the effects of inbreeding and genetic drift, it is essential to initiate brood stock from a sufficient number of founders. Sex ratio is also critical as, for example, a brood stock of 4 males and 100 females will lose as much variability due to drift as a population of 8 males and 8 females, everything else being equal. The same consideration concerning the effective population size (Ne) used for introduction, transfer or stocking-apply for hatchery brood stocks and for the collection of individuals taken from the wild for immediate release. There is a frequent considerable overestimated of the Ne of founder fish due to high rates of mortality commonly encountered during colonization of new habitats. On another hand, recent studies put into evidence that intense selective mortality occurs in the earliest larval stages in offspring from fish taken from the wild, thus affecting genetic changes over a single generation of captivity.

Moreover, recommendations were made that aquaculture breeding programs should be designed to develop numerous stocks specially adapted to local environments. This may minimize genetic impact of aquacultural stocks on wild stocks while producing economic benefits for individual farmers and conserving the genetic variation among stocks that is necessary for long-term successful culture.

The potential problem of the accidental release of aquaculture stocks is demonstrated by the example of Atlantic salmon (*Salmo salar*) in Norway. Currently about 70% of the Atlantic salmon farmed in Norway comes from a single breed developed locally. The number of escaped fish from these operations increased dramatically throughout the 1980s. For example, an estimated 1.2 million salmon escaped from Norwegian fish farms during storms in 1988 and 1989. These accidental releases are equivalent to the total annual catch of wild Atlantic salmon in Norway.

On the other side, marked phenotypic differentiation was observed in the clupeid *Limnothrissa miodon* after its introduction to the man-made Lake Kariba from Lake Tanganyika. In 1967, 360 000 fry were introduced and the species established itself quickly. But from initial catches, it was clear that *Limnothrissa* in Lake Kariba was conspicuously different in size and life history characteristics from the source population in Lake Tanganyika. Several hypotheses were proposed to explain the smaller size, earlier maturity and higher mortality, one of them being that the species changed genetically during or after the introduction. As a matter of fact, rapid genetic changes are predicted to occur in populations founded by only a few individuals and although a large number of fry were introduced here, it does not necessarily follow that the genetically effective founder population was equally large.

An allozyme electrophoresis and a PCR-based RFLP analysis of mt DNA (ND 5/6 genes) on samples from the source and introduced populations showed no genetic differentiation during or after introduction of *Limnothrissa miodon* to Lake Kariba which is not the case for Lake Kivu where the introduction of *Limnothrissa* was associated with a significant reduction in mt DNA haplotype diversity. In Lake Kivu, even though 57 400 fry were introduced, high mortality rates and low spawning success probably reduced the effective size of the founder population to tens rather than thousands of individuals, resulting in founder effect and a reduction in genetic diversity.

Other than genetical explanations for the small size of Lake Kariba *Limnothrissa* was given. The most likely explanation to account for biological differentiation was high predation in Lake Kariba where predators make up a high proportion of the fish stock. Under such conditions, the small size of *Limnothrissa* in Lake Kariba is a distinct advantage, since by maturing early and at small size, fish are able to maintain a constant proportion of mature adults in the stocks despite intense predation on adults. Small body size thereby redistributes more energy to reproduction, resulting in relatively higher fecundities. Other explanations suggest that during the day, the fish try to descend into deeper water but, the oxycline being much shallower in Lake Kariba than in lakes Tanganyika and Kivu, the fish may spend the day in oxygen-poor water, which could slow down their growth considerably. Other possible explanations refer to the lack of suitable prey organisms for larger *Limnothrissa*.

Then, differences observed appear to be primarily phenotypic and it can be considered that the success of this species as a colonizer is related to its phenotypic flexibility in feeding, growth and life history traits. Indeed, high phenotypic flexibility does not only permit a rapid colonization of a new environment, but it does also reduce the chances of progressive and irreversible genetic changes resulting in a narrower scope of response to changes in environmental conditions such as predation and harvesting intensities. This illustration could be of major importance for the reflection surrounding fish introductions, as fish populations are the most phenotypically diverse of all vertebrates, with coefficients of variation in phenotypic characters often far greater than 10%, compared with average values of less than 5% in most other vertebrates.

Examples of genetic deterioration due to alien fish species introductions and transfers within aquaculture activities are very numerous. The environmental impact of such deterioration is evident as aquaculture facilities are, except very rare situations, connected with the hydrographic system (rivers, lakes) and both accidental stocking and interactions with wild populations may occur quite often. The most frequent cases concern introgressive hybridization and loss of genetic variability. When introductions concern species coming from other continents, due to transportation constraints, the founder stock has consisted usually in a very few number of individuals which, moreover, were often closely related (full sibs, parent-offspring, half-sibs).

Examples of such situations can be found in cultured *Oreochromis* species in Asia, which is, by far, the main tilapias producer since the 1980s. The occurrence of *Oreochromis mossambicus* in Asia was reported for the first time in 1938 in Indonesia, on Java Island, where it might have been introduced in the 1930s. The stock of “Java tilapia” consisted only in 2 females and 3 males and all the *O. mossambicus* introduced to almost all the East and Southeast Asian countries might have come from this very narrow founder stock. This could explain the poor aquaculture performance of the species.

Most of introductions of *Oreochromis niloticus* to Asian countries have been made within Asia except for a very few number of cases (Japan, China) where direct introductions from Africa were carried out. If the stock introduced from Egypt to Japan in 1962 seems to have maintained a high genetic variability (observed heterozigozity = 0.09), the Thailand stock introduced from Japan in 1965 showed in the 1980s a very poor genetic variability (observed heterozygoty = 0.01), which indicates that a bottleneck has occurred at some stage. From Thailand, *Oreochromis niloticus* spread to many other Asian countries, among which the Philippines where this “strain” contributed very significantly to the tremendous development of the tilapias aquaculture industry, reaching an annual production of nearly 100 000 t in the 1990s.

Moreover, several surveys conducted in the Philippines on supposed “pure” *O. niloticus* cultured stocks put into evidence a high level of introgressive hybridization by *Oreochromis mossambicus* which justified the implementation of breeding programs based on the use of pure strains that had to be reintroduced.

4.5 Introduction of Parasites, Pathogens, and Diseases

The importation of parasites, pathogens and diseases can be made via introduced fish, even those not intended for release. It is one of the most persistent risks inherent with movements of living organisms around the world. Nematode parasites of the genus *Anguillicola* have been introduced into Europe with oriental eels, *Anguilla* spp., intended for human consumption and not for stocking into natural waters. Nevertheless, the nematode escaped and has since spread rapidly through the waters of Northern Europe. Another example of such disease introduced through fish not intended to be stocked or cultivated but for direct human consumption purposes concerns infections haematopoietic necrosis which was probably introduced with un-gutted Pacific salmon carcasses and which has been recognized in France in the late 1980s.

Many of the diseases of the salmonids that infect hatchery-reared fish and also occur in he wild have been imported. Furonculosis appeared both in Europe and South America following the introduction of rainbow trout from Western North America. Infectious dropsy of cyprinids spread rapidly through Western Europe after a common carp transfer from the former Yugoslavia in the 1930s. More recently, the North American fathead minnow, *Pimephales promelas*, introduced *Yersinia ruckeri*, the causative agent of red mouth disease to parts of Northern Europe, due to uncontrolled shipments.

The pathogens of several diseases, such as infectious pancreatic necrosis, infectious haematopoietic necrosis and bacterial kidney disease can be transmitted vertically via the gametes, so that unfertilized sperm, eggs and embryos, as well as adult fish, are all potential vectors. More over, some pathogens are not group-specific and they can, and do, infect native species when introduced by exotics. For example, *Aeromonas salmonicida* is effective both with salmonids and cyprinids. Frequently, pathogens are more serious in atypical hosts. For example, *Myxosoma cerebralis* is a harmless common parasite of brown trout, but a proliferative kidney disease of salmonids such as rainbow trout (whirling disease).

Most of these examples are drawn from countries where the state of knowledge of fish hygiene is relatively advanced and controls are enforced. However, these and other diseases could also have been imported into other parts of the world and so far remain unreported. In particular, pathogens introduction associated to tropical fish culture is a little studied topic.

4.6 Socioeconomic Impact

Impacts of introduction do not only concern biological and ecological parameters, but might also directly or indirectly affect socioeconomical factors. This could occur when an undesirable introduced species replaces a highly valuable native fish. This situation was observed with the ruffe *Gymnocephalus cernuus* in Europe (Lake Constance) or in North America (Laurentian Great Lakes).

In Lake Victoria, the fishery was based on the use of small mesh gill nets before introduction of *Lates niloticus*, as most of the captured fishes were small cichlids. When these native species declined and got replaced by Nile perch, fishermen might have had to re-equip with nets of the appropriate size. But this might have exceeded the financial possibilities of many, and consequently could have induced a shift from subsistence fisheries to commercial operations for export. But this theory is subject to debate and controversy and whatever the truth, appreciation of such impacts is quite subjective.

Where local economics are dependent on the rearing of fish in captivity for human consumption, their financial vulnerability is considerable. Introduction of exotic species could have catastrophic socioeconomical consequences if it involves negative impacts and particularly the occurrence of new disease or the genetic deterioration of cultured brood stocks. Since aquaculturists are largely dependant on exchanging genetic material of their stock by means of introductions, care needs to be taken to minimize the inherent risks.

4.7 General Overview of Fish Introductions Impacts

Introducing a new species into an aquatic ecosystem is never a neutral action but all introductions practiced in the past cannot be considered equally. Fish transfers can be classified into three categories, depending on the balance between costs and benefits: positive impact, balanced impact and negative impact.

In the first category is the introduction of *Limnothrissa miodon* in Lake Kivu and Lake Kariba, which has not been accompanied by any known detrimental impact on ecosystem, but in return has allowed a major increase of fisheries production (< 5 000 $t.year^{-1}$ in 1972; > 30 000 $t.year^{-1}$ in 1990 in Lake Kariba). This absence of apparent effect on other fish species and environment probably reflects the simple fish fauna, which occurred naturally in those lakes. Kariba is a man-made lake whose original fauna was derived from riverine species, none of which successfully exploited the pelagic region of this huge reservoir, while Lake Kivu had an extremely impoverished fauna as the result of catastrophic fish kills related to volcanic activity in its recent history. The introduction of this fish in those lakes could be considered like a reasonable and relevant choice.

Another positive introduction is that of *Oreochromis mossambicus* in Parakrama Samudra reservoir (Sri Lanka), where annual fish production increased from less than 10 $kg.ha^{-1}$ in 1953 to 450–500 $kg.ha^{-1}$ in 1978. Indigenous fishes have not been negatively affected and, on the contrary, it appears that they have benefited from the presence of tilapias. It seems likely that the high densities of tilapia speed up mineralization thus enhancing plant growth. Cyprinidae, which comprise most of the indigenous fish component in the catch, benefit from eutrophication. Parakrama Samudra supports a very dense fish eating bird population and also indigenous piscivorous Siluridae and Channidae. Tilapias probably reduce predation pressure on indigenous carps. Overall, the average fish yields in Sri Lankan reservoir fisheries is about 300 $kg.ha^{-1}.y^{-1}$ and *Oreochromis mossambicus*, introduced in 1952, accounts for over 70% of the total landings and do not compete with native species.

Many cases of exotic fish introductions for aquaculture purposes can be considered as having resulted, globally, in positive, or even highly positive, impact. *Oncorhynchus mykiss* introduced to France from North America in 1884, initially for sport fishing, allowed this country to become the first aquaculture producer of this species (annual production over 50 000 t).

No major negative impact was recorded due to introduction and wide domestication of rainbow trout both on the environment and on other wild or cultivated species in France. *Oncorhynchus mykiss* is considered as an un-acclimatized species as successful reproduction in the wild does generally not occur naturally and, when it occurs, domesticated populations reproduce during autumn leading to poor survival of fry during winter characterized by adverse hydrological and poor feeding conditions in the rivers.

Introduction of Nile tilapia, *Oreochromis niloticus* to Asia during he 1960s and the 1970s had a tremendous impact on the aquaculture industry of several Asian countries. Largely disseminated within Asia from countries like Japan or Thailand, this species has become, despite its exotic status (native range: Africa), like a native fish. As a matter of fact, the widest utilized strains of *O. niloticus* for aquaculture have been denominated from the name of the place or of the country where brood stock maintenance (rather than genetic improvement) has been achieved: the "Singapore strain," the "Taiwan strain," the "Thai strain," (also called "Chitralada strain," from the name of the Thai royal palace where it was stocked after introduction from Japan). Philippines, to where Nile tilapia was introduced in 1972, became in the late 1980s the first cultured tilapias producer in the world (annual production of about 100 000 t), now overtopped by China (approximately 400 000 t). Aquaculture of this exotic species became in the Philippines much more than only a source of protein for human consumption. It allowed an autochthonous, specific, original and fruitful basic research and aquaculture technology generation to develop on an exotic introduced fish and to expand widely outside Philippines boundaries. Among the original outputs, the main technologies concern monosex progenies production through precocious hormonal sex reversal, mass production of fry in soft technology facilities such as "hapas" (fine-mesh net cages) or daily collection of fry and appropriate brood stock management in traditional earthen ponds.

This example is an outstanding demonstration that, if the introduction of exotic fish has generally been considered as a trend for food producers to cut risk by importing technologies that were already established, going along with the imported species, the exact opposite situation may occur and, moreover, at a very large scale. Another historical example is given by the first artificial reproduction of common carp, *Cyprinus carpio*, by inducing ovulation using pituitary extracts removed from other mature fish, achieved by von Ihering in 1934, in Brazil, where this very species is definitely an exotic one.

A typical balanced impact introduction could be Lake Victoria. Negative consequences of introduction have already been considered: decline of numerous native haplochromines and subsequent major ecological consequences. But, on the other side, the introduction of *Lates niloticus* and *Oreochromis niloticus* into Lake Victoria was aimed at improving fisheries. Indeed, the total catch of the Nile perch reached more than 300 000 t by the end of the 1980s, whereas landings of *O. Niloticus* reached 60 000–70 000 t in 1990. The total landing (500 000 t in 1990) represent five times the mean production observed before introduction.

Two frequently quoted examples of negative introductions are that of ruffe *Gymnocephalus cernuus* in North American Great Lakes and common carp *Cyprinus carpio* in Australia. The ruffe, *Gymnocephalus cernuus*, is a small, bottom-dwelling, and largely benthivorous percid found throughout much of Europe and Northern Asia where it has long been considered to have very little or no value for commercial or recreational fisheries. However, it has been recently accidentally introduced in several European and North American places, in particular in the Laurentian Great Lakes with the ballast of oceangoing vessels. This species is susceptible to have negative effects on commercially important or rare fish species, particularly whitefishes of the genus *Coregonus* and perch of the genus *Perca*. Effects on the former genus may act through egg predation, while those on the latter may involve competition for food. In such lakes, abundant ruffe populations have resulted within only a few years.

In Australia, hybridization between two or possibly more imported varieties of the European carp, *Cyprinus carpio*, has given rise to the vigorous and aggressive "Boolara" strain which spread explosively in the 1960s and 1970s, becoming far more widespread and problematic than the other originally introduced stocks which remained confined to their original sites of introduction.

5. Codes of Practice

Temptation is great for many ecologists to avoid the numerous risks inherent in introductions and transfers of aquatic living organisms by prohibiting all further movements of biotic material. But this solution is overly simplistic and unrealistic because further introductions will continue to be needed to sustain fisheries and aquaculture development and because established commercial and private practices make such prohibition virtually impossible to enforce. Consequently, it appears very important for individual countries to adopt regulations and procedures, which will minimize the risks arising from introductions.

Early efforts were promoted in the early 1970s in order to propose codes of practice. Such efforts were built upon by a number of international organizations, especially ICES and FAO (chiefly through EIFAC). However, until recently, such codes have been used only rarely in practice and remained mainly at the stage of concepts and recommendations within international workshops.

The FAO "Precautionary approach to species introduction," elaborated in 1995 in relation with the ICES "Code of Practice" (1994) aims at providing a working framework for FAO Regional Fishery Bodies and are a part of general "Technical guidelines for responsible fisheries." The code is still being evolved and supplementary material is being produced by FAO to assist in its implementation mainly in developing countries. It considers both deliberate and unintended introductions. Prior to any introduction, any proposal should consider the purpose and objectives of the introduction, all relevant biological, ecological and genetic data of the species in the target area likely to be affected, an analysis of potential impacts (ecological, genetic and disease, consequences of its spread) at the introduction site and, finally, a qualitative and, whenever possible, a quantitative risk assessment. If competent authorities approve this proposal a brood stock should be established at a suitable quarantine site whose effluents are appropriately sterilized and the isolated first generation individuals, free of disease should be released in the wild of a limited scale in small number and studies of the introduction in the new environment should be continued. If not possible, due for example to some commercial practice, the approach should consist in at least periodic inspection prior to exportation and after exportation and quarantining, inspection and control whenever possible and where appropriate. For unintended introductions, particularly that achieved via ballast water, several technologies are available: non-release of ballast, ballast water exchange in approved areas, preventing or minimizing uptake of contaminated water or sediment, special ballasting facilities on shore, education of crews about ballast water management procedures and treatments of ballast water, including changes in temperature, and salinity or use of chemical biocides.

Taking into account the little information existing on the genetic, ecological and other effects of the release of genetically modified organisms (GMOs) into the natural environment, it is highly recommended to strongly regulate such releases, and to notify competent international organizations (ICES, FAO) at an early stage before such releases are made. This notification should include a risk assessment of the effects of this release on the environment and on natural populations and it is recommended that initial releases of GMOs be reproductively sterile in order to minimize impacts on the genetic structure of natural populations.

Further research is needed for each introduction. For deliberate introductions, research activities should aim at assessing the biology and ecology of the intended introduction, at preparing a hazard assessment and at examining the species, within its home range. Some technological intervention can be used, such as the use of hatcheries and quarantine stations to reduce the chances of spread of disease, the use of sterile organisms to reduce the chance of interbreeding with natural fish stocks, the identification of the genetic stock to reduce or prevent genetic changes in the fishery resource, the monitoring of health of the introduced species, and the use of limited pilot scale introductions to assess impacts and performances of exotic species. For unintended introductions, active research should take place and continue on practical methods for treating organisms in ballast water and sediment, on the study of dynamics of target species in voyage, on the study of algal cysts in ships ballast sediment and in port areas, on the effectiveness of re-ballasting activities and on designing changes to ballast water tank to kill or control harmful species and on vessel design in order to facilitate the treatment, and handling of ballast sediments and water.

6. Conclusion and Prospects

Considering movements of aquatic living organisms in general and of fish species particularly, in terms of both time and space scales, it can be assumed that international species transfers and introductions have resulted in much more beneficial impacts than negative ones. These movements can definitively be considered as efficient tools for increasing protein production, improving human nutrition and generating income and employment. The contribution of introduced and transferred species to global aquaculture production is very significant and explains the relatively low number of cultivated aquatic species: only 7 species of aquatic plants and animals account for more than 50% of the total aquaculture production. This situation does not differ from terrestrial ecosystems where, among 4800 cultivated plant species, only 4 species account for 50% of the total food crops (wheat, maize, rice and potatoes). The use of exotic fish for improving wild stocks, and consequently enhancing fisheries, is a common practice which has, in many cases, resulted in very spectacular results such as, for example, the introduction of tilapias species into reservoirs or natural water bodies of Asia, Africa and America. The use of transferred or introduced fish species as tools for biomanipulation of lakes aiming at reducing eutrophication becomes a current practice particularly in temperate countries.

But species transfers can also promote some extremely negative environmental impact, some of which are even qualified of ecological disasters. Introduction of Nile perch in Lake Victoria, who's positive and negatives impacts are however quite balanced, is frequently given as a symbolic illustration of such environmental risks. Besides the inestimable loss of biodiversity, the ecological degradation observed in this lake shows mostly how an introduction aimed at improving a given existing situation can entail unexpected and uncontrollable effects. It can even, in some extreme situations ruin a well-established economy. This shows how important it is to establish and use an efficient code of practice, in order to reduce the risks of adverse effects that could arise from such operations. Research and education will most probably be of major importance to allow responsible fisheries and aquaculture to be conducted by all the concerned operators, much more than edicts and strict regulations that are, evidently, not applied.

Introduction of exotic species has not the same signification worldwide. If rural societies of developing countries are ready to tolerate quite considerable environmental change in favor of immediate solutions to food deficiencies, post-industrial societies tend to put outstanding emphasis on the protection of the environment and on biodiversity preservation and thus are over cautious about any further species movement. The units of measurement of introductions impacts are consequently almost opposite in both situations.

Nowadays, the public opinion and the governments are increasingly aware of this problem, and moreover the number of new deliberate introductions is decreasing as most practical introductions have already been made. This could mean that risks are limited to unintended introduction but, in fact, this may not be the case in the future. As a matter of fact, emphasis is currently put on domestication of "new" species of aquaculture interest. This could revitalize fish movements if breeding of some highly valuable species was to be mastered. Another potential source of fish movements could be provided by hybrids deliberately produced to gather advantages of two or more already existing species. Last but not least, the development of genetically modified organisms may have a certain level of risk for wild species and global environment and is often negatively perceived by consumers.

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Biographical Sketches

Jerome Lazard graduated from Montpellier University (Ph.D. Aquatic Ecology) and Paris 12 (HDR). He is currently appointed to the French government-owned *Centre de Coopération Internationale en Recherche Agronomique pour le Développement* (CIRAD) in Montpellier (France) where he is in charge of the Aquaculture Research Unit. He spent 15 years as a scientist in West Africa where he implemented and carried out R. and D. fish culture projects, mainly based on tilapia aquaculture. Once back in France, he did several missions both as a consultant for building research and development strategies in the field of inland fish culture in many tropical countries (Africa, Asia, South America) and for the implementation of scientific collaborative programs in this field. His research topics focus on tropical fish culture production systems. He has been awarded the silver-gilt medal of the French Academy of Agriculture and he his a Life-Member of the Society of Aquaculture Engineers of the Philippines. He is the author of publications on tilapia aquaculture and fish culture projects analysis.

Lionel Dabbadie graduated from the Agronomic School of Montpellier (France) with a doctorate from the University of Paris 6, has been working on fish farming in Africa and Brazil for the French government-owned *Centre de Coopération Internationale en Recherche Agronomique pour le Développement* (CIRAD). He has been awarded the silver medal of the French Academy of Agriculture for his work on the pond dynamics in the framework of African extensive fish farms. He is presently working in the Brazilian Tocantins State on a project of culture of Amazonian native fish species, particularly on the endangered Osteoglossid *Arapaima gigas*, in cooperation with the Tocantins government and private operators.

Table 1. Number of successful introductions by geographic region recorded as of 1992.

Number of successfully introduced species	**ASIA**	**AFRICA**	**AMERICA**	**OCEANIA (Including Australia)**	**EUROP E**	**TOTAL**
> 15	1	2	2	2		7 (8 %)
11–15	2	3	4	3		12 (13 %)
5–10	6	4	6	1		17 (19 %)
1–5	5	16	17	17		55 (60 %)
Total	14	25	29	23		
Most permissive countries	Philippines (22) India (13) Sri Lanka (13)	Madagascar (21) Zimbabwe (14) Kenya (14)	Colombia (33) Puerto Rico (21) Panama (14)	Hawaiian Islands (42) Australia (27) Papua New Guinea (15) Fiji (14) Mariana Islands (11)	Australia (27)	

Table 2. Changes in purpose of introductions expressed as percentage within each decade for each major categorie of use (Welcomme, 1988)

Decade	**Aquaculture**	**Sport**	**Fishery improvement**	**Ornament**	**Control**	**Accident**	**Unknown**
1850	25.0			25.0		25.0	25.0
1860	20.0	50.0	10.0	10.0			10.0
1870	12.5	37.5	25.0	4.2		12.5	8.3
1880	35.7	25.0	10.7			10.7	17.9
1890	36.4	31.8	13.6	6.8		2.3	9.1
1900	29.6	29.6	18.5	7.4	3.7	1.9	9.3
1910	37.0	25.9	11.1		7.4	7.4	11.1
1920	14.5	25.5	10.9	3.6	9.1	21.8	14.5
1930	17.4	24.6	20.3	2.9	8.7	10.1	15.9
1940	25.0	25.0	13.3	1.7	8.3	6.7	20.0
1950	43.6	10.5	19.3	0.6	8.3	2.8	14.9
1960	45.7	8.2	11.4	1.8	10.5	10.0	12.3
1970	59.6	8.8	11.4	0.5	8.3	5.2	6.2
1980	69.4	6.5	8.1	0.0	0.0	4.8	9.7