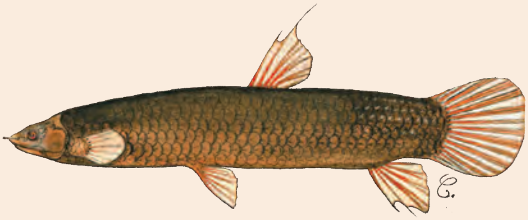
Fish culture



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Although Egyptians were rearing the tilapia *Oreochromis niloticus* in artificial ponds nearly 4,000 years ago, the African continent, unlike Asia, has no tradition of fish culture. In the early twentieth century, aquaculture was still virtually unknown there. The first attempts to develop it date back to the 1940s.

These initial attempts were part of a broader goal to diversify the sources of animal protein in order to promote the food self-sufficiency of rural populations. When pilot tests with tilapia at the Kipopo station created in 1949 in the former Belgian Congo yielded promising results, colonial administrators proceeded with expanding these activities. By the end of the 1960s, there were a number of such research/demonstration stations dotted across the continent: Djoumouna (Congo), Landjia (Central African Republic), Foumban (Cameroon), Bouaké (Côte d'Ivoire), Sagana (Kenya), Anamalazaotra & Ampamaherana (Madagascar), Kanjasi (Uganda), Chilanga (Zambia), Henderson (Zimbabwe), and Domasi (Malawi).

The first tests conducted at these stations involved species that have now been abandoned because of poor yields: *Coptodon zillii, Coptodon rendalli, Sarotherodon galilaeus, Oreochromis mossambicus* and *Oreochromis macrochir*. It took until the 1970s for breeders to take notice of the zootechnical performance of *Oreochromis niloticus* and its hybrids with various neighbouring species, as they far outclassed that of most other tilapias. It was also during this time that other species with fish culture potential began to be identified: *O. aureus, O. andersonii, Sarotherodon melanotheron*, the African sharptooth catfish (*Clarias gariepinus*), the African boneytongue (*Heterotis niloticus*) and the alien common carp (*Cyprinus carpio*).

Despite massive aid to promote fish farming in Africa to mirror the Asian example, results were disappointing. In 2013, estimated aquaculture production was only 1.4 million tonnes for sub-Saharan Africa whereas global production stood at 66.6 million tonnes (FAO, 2014).

Following the FAO report (FAO, 2014) the sub-Saharan Africa region continues to be a minor player in aquaculture despite its natural potential. Even aquaculture of tilapia, which is native to the continent, has not developed significantly. Nigeria leads in the region, with reported production of 278,000 tonnes of catfish, tilapia and other freshwater fishes (source: FishStat Plus). In North Africa, Egypt is by far the dominant country in terms of production (providing 943,000 tonnes) and is now the second biggest tilapia producer after China and the world's top producer of mullets.

Although it is very difficult to obtain reliable figures for actual production, in a context where the trade of aquatic products is often done informally, we are just beginning to realize, in the early 21st century, the continent's vast potential for aquaculture development.

Two reviews (Moehl *et al.* 2006; Brummett *et al.* 2008) distinguished between several types of fish culture on the basis of development criteria: extensive, artisanal, small/medium-scale commercial and large-scale commercial. All categories of aquaculture have the potential to be profitable and sustainable but it is necessary to evaluate which category must be promoted or assessed against the overall objectives defined for this sector.

Different types of African fish culture

Extensive aquaculture

All over the continent, rural communities utilize waterbodies, either temporarily or permanently, for fish production. Often, this simply involves the periodic capture of wild fish, but increasingly, productivity is being enhanced through the use of stocking or other aquaculture practices. In the Guinea rainforests, for example, controlled stocking of small dams (2,000-10,000 m^2) with or without fertilization is being used to increase typical background productivity of normally no more than 100 kg/ha up to between 600 and 2,500 kg/ha/y (APDRA-F, 2007) (see box "Extensive fish culture in the Guinea forest region: a model of integrated development and of rice-fish production"). In the Lower Shire River valley of Malawi, local communities stock otherwise fishless temporary waterbodies, locally known as thamandas, with fingerling tilapias and catfishes, producing an average of 600 kg/ha (range 300-1,575 kg/ha) in a 2-3 month growing season (Chikafumbwa *et al.*, 1998). Acadjas have been used for centuries in West and Central Africa for attracting and nourishing fish (see box "Acadjas").

In Burkina Faso, traditional reservoir management systems have evolved in the direction of restocking after annual drying with fingerlings of *Oreochromis niloticus, Labeo coubie* and/or *Clarias gariepinus* produced through artificial reproduction of adults captured at harvest and held over the dry season (Baijot

EXTENSIVE FISH CULTURE IN THE GUINEA FOREST REGION: A MODEL OF INTEGRATED DEVELOPMENT AND OF RICE-FISH PRODUCTION

Highly developed in Asia, rice-fish production is almost inexistent in Africa.
It consists of farming rice and fish in the same rice fields.

While it often produces small fish, rizi-pisciculture nonetheless remains interesting because it can achieve adequate volumes (1000 kg/ha/y) at a low cost, even if they do not approach yields obtained from intensive production, which can be 10 to 20 times greater.

This practice still allows a farmer to diversify production without expanding the cultivated area while increasing protein production.

In the early 2000s, the IRD (French National Research Institute for Sustainable Development) and the MPA (Ministère des Pêches et de l'Aquaculture of Guinea) conducted an experiment with the SOGUIPAH (SOciété GUInéene de PAlmier à huile et d'Hévéa) in order to establish an extensive tilapia (mainly *Oreochromis niloticus*)/rice production system that could be easily adopted by farmers (Extensive pisciculture in Forested Guinea in the region of N'Zérékoré, south-eastern Guinea). The programme's ultimate goal was, obviously, to make the production system rapidly autonomous.

The fish stocking of rice fields requires the production of fry first of all. For an untrained farmer, mastering the simultaneous problems of fry production and fish fattening represented a difficulty that was compounded by the length of the full cycle from birth to harvest, 13 months on average, which is much too long.

The strategy adopted for the programme was thus to split the processes into two parts: the production of fry, a task entrusted to women, and the fattening of fish in the rice field, carried out by the farmers.

Fry production was carried out by plotting out non-cultivated sections in the rice fields, where breeding stock would be placed, in general 50 males and 100 females for 400 m^2. The fry produced naturally enter the areas planted with rice for food and shelter. After four months, the fry are harvested and transferred to their fattening site. This last stage takes 6 months, a period similar to other agricultural activities.

This activity creates a non-negligible additional income for farmers as it brings in 1000 euros/ha/year on average. This project led to an agricultural activity that is sustained in the N'Zérékoré region. It received support in 2008 from the French Embassy (amounting to 3 million euros) and continues to be supported by NGOs including APDRA (Association Pisciculture et Développement Rural en Afrique tropicale humide).

"ACADJAS"

The term "acadja" refers to a fishing technique practised in the lagoons of Benin and a few other West African lagoons (Pliya, 1980).
It is an artificial reef wherein arrangements of branches are placed in shallow waters, where they encourage the development of epiphytes and microorganisms and increase natural productivity.
The acadja also provides shelter to juveniles of several species, notably lagoonal cichlids.

An estimated 30 to 40 tonnes of branches are needed to construct a hectare of acadja (Welcomme, 1972b), and annual renewal is 50% as the wood is attacked by shipworms.
This has a non-negligible impact on surrounding terrestrial vegetation.

The "acadja-enclos" is a fish farming method derived from traditional acadja fisheries, in which the branches are replaced by bamboos planted vertically in lagoon sediment.
Fish stocking with *Sarotherodon melanotheron* tilapia may be natural or artificial, and production can reach 3 to 8 tonnes per hectare per year in the Ébrié lagoon, with no food supplements needed (Hem & Avit, 1994 ; Hem *et al.*, 1994).

et al., 1994), increasing productivity from 50-100 kg/ha/y up to over 600 kg/ha/y. In Niger, natural temporary waterbodies stocked with *C. gariepinus* can produce up to 200 kg/ha/y depending on rainfall, returning an average of $1,400 per person per year to the fish farmers/fishermen involved in their management (Doray *et al.*, 2002). In Southern and Eastern Africa, there were between 50,000 and 100,000 small dams producing between 1 and 3 million tonnes of fish per year, most of which is consumed by rural communities (Haight, 1994).

These types of decentralized fish production systems could have broad applicability across Africa's vast dry savannah area, including all or parts of virtually every African country. While such extensive aquaculture may not be the most productive in terms of fish output, the additional benefits of water table replenishment, flooding, and erosion control and possibilities for multiple uses such as livestock watering, irrigation, and capture fisheries could return substantial benefits to local communities and help in the fight against desertification (Roggeri, 1995), if ownership and management arrangements can be negotiated among the various and sometimes disparate user-groups.

Artisanal farming systems

Over 90% of African fish farmers operate one or a few earthen ponds of generally less than 500 m^2 in surface area, constructed and operated with family labour (King, 1993). These ponds typically produce between 300-1000 kg/ha (15-50 kg per crop), on an annual harvest cycle usually corresponding to fingerling availability, water supply or local demand. About half of the output from these systems is consumed by the family and half sold or bartered to neighbours. Little of the crop is sold for cash, either due to lack of access to wealthier markets or out of a need to meet more local food security priorities (Brummett, 2000). In these systems, the fishpond plays a role similar to that of the chicken coops, pigsties, fruit tree orchards, herb gardens and other micro-enterprises undertaken by smallholders to generate small amount of cash for emergencies, school fees, etc. (Satia *et al.*, 1992).

Few of the inputs for artisanal aquaculture are purchased, productivity being based almost entirely on composts, manures and other organic materials found on the farm and recycled through the pond. The best fish productivity in such systems in Malawi, where they have been intensively studied, is about 1,500 kg/ha/y, mostly of small tilapias (Brummett & Noble, 1995). These "farmponds" are generally integrated into other food production systems such as vegetable gardens where they serve as sources of emergency irrigation water and as bio-processors for by-products and wastes, turning low quality materials into valuable fish at minimal cost. In Malawi, farms with integrated fishponds produce almost six times the cash generated by the typical smallholder (Brummett & Noble, 1995). Similar systems exist throughout the continent, producing thousands of tonnes of fish annually for rural families.

Diversifying a smallholding by integrating aquaculture can also affect the ecological sustainability and economic durability of small farms. In Malawi, a serious drought from 1991 through 1995 had a major negative impact on smallholding agriculture. Yet in all cases studied, even though staple crops failed and farmers lost money, the integrated fishpond sustained the farm. By retaining water on the land, ponds enabled farmers to continue food production and balance economic losses on seasonal cropland. For example, in the 1993/94 season, when only 60% of normal rain fell, average net cash income to integrated farms was 18% higher than to non-integrated farms (Brummett & Chikafumbwa, 1995).

In areas with high population pressure, integrated aquaculture systems can help keep people alive and on the land producing food for themselves and their communities. However, as they generate minimal cash revenues and therefore no liquid capital for reinvestment and expansion, especially the purchase of inputs, they create little or no economic growth (Delgado *et al.*, 1998).

Small and medium-scale enterprises (SME)

Many of the more entrepreneurial farmers have seen the potential to diversify their traditional cash-crop investments (coffee, tea, cacao, bananas, etc.) by shifting some capital out of these traditional cash-crops to aquaculture. These farmers build more ponds, use higher technology, employ hired labour, purchase fingerlings and/or inputs (esp. feeds and/or fertilizers) and understand the concept of cash-flow. Rather than eat or give their fish away, they transport them to a town or city where wealthier consumers pay cash. The main difference, however, between SME and artisanal farmers is motivation; artisanal farmers primarily seek food security and farm diversification, while SME farmers seek cash, often at the expense of diversity and, sometimes, sustainability (Brummett *et al.*, 2005).

SME exploitations are subject to the plethora of social leveling mechanisms common in rural African communities and are usually obliged to sacrifice a percentage of their production (±30% in Cameroon according to Brummett *et al.* (2005)) to maintain their position in local society and minimize the threat of theft and/or sabotage (Harrison *et al.*, 1994). Other constraints include high transportation costs (for farmers distant from wealthier urban markets) and the lack of marketing infrastructure, especially ice plants and clean facilities, which limit the ability of producers to negotiate decent prices as fish start to decay towards the end of the day (Brummett, 2000).

In South Africa, the SME segment of aquaculture sector is relatively well-developed. The Aquaculture Association of Southern Africa (www.aasa-aqua.co.za) produces a newsletter and holds regular meetings funded by a growing number of secondary beneficiaries of aquaculture development, including banks, feed mills and processing plants.

Aquaculture SMEs are also expanding in Nigeria where over 2,000 farms with an estimated 60,000 ha under water produce 25-30,000 TPA (AIFP, 2004), mostly of sharptooth catfish, which are highly prized in the Nigerian market (Moehl, 2003). According to the farmers, this remarkable growth was achieved with virtually no support from the Nigerian national aquaculture research and extension services.

Even more recently, small and medium-scale aquaculture investments have been growing in Cameroon, Ghana, Uganda, Angola, DR Congo, Zambia and Kenya. Once a node of (mostly French) donor-assisted SME development, Côte d'Ivoire has, since the coup d'état in 2000, reverted to mostly artisanal production.

In general, however, SMEs have received little attention from African governments and even less from international donors, as they are not perceived to represent "the poor".

Large scale commercial

There are a few successful large-scale, commercial aquaculture investments in Africa, most notably in Tanzania (racks, seaweeds, export), Mozambique (ponds, shrimp, export), Zambia (ponds, tilapia, local markets), Zimbabwe (cages, tilapia, export), Ghana (cages, tilapia, local markets) with new investments coming on line in Uganda (cages, tilapia, export) and Kenya (cages, tilapia, local markets). Most of these have been built using foreign or foreign-earned capital and rely on foreign or foreign-trained technical expertise. Although all are not yet at full capacity, these farms each have planned production in excess of 1,000 TPA (Tonnes Production per Annum) and are targeting markets in larger African cities and/or the ever-growing international tilapia trade. All are vertically integrated to one extent or another, including feed manufacture, fingerling production, selective breeding programs, processing plants, retail sales outlets (local and overseas) in addition to production facilities.

Currently dominating this sector are cage-based tilapia systems using modified[1] Scandinavian salmon cage technology, most notably in Volta Lake and Lake Kariba. The largest of these is Lake Harvest, Ltd. based in Kariba, Zimbabwe where 3,000 TPA of 750 g tilapia are grown in 500 m^3 cages at a density of 50 kg/m^3. The company owns a state of the art processing plant which produces fresh fillets for air shipment to luxury markets in Europe.

Most African governments welcome large-scale aquaculture investments as employers, foreign exchange earners and, for those targeting local markets, fish suppliers. Access to land and water resources is generally good and most environmental regulatory bodies have been willing to negotiate permits. On the downside, aquaculture production systems are not highly labour-intensive, requiring between 0.05 and 0.1 person-year per tonne of fish produced. While this may be an important incentive for producers, maximizing the economic growth potential of aquaculture will require that governments interested in rural poverty alleviation encourage the development of an horizontally integrated aquaculture industry where technical assistance providers, feed growers and manufacturers, equipment and input suppliers and marketing chains create additional employment and business opportunities.

Ecological intensification and IMTA (Integrated Multi Trophic Aquaculture)

There are many definitions for the concept of ecological intensification (Dugué *et al.*, 2012) but it can be summarized as the use of natural mechanisms or ecological processes to increase production while using fewer inputs.

Sustainable intensification is also used sometimes (FAO, 2011), as compromises have to be made between increased short-term production while maintaining the productive capacities of socio-agro-ecosystems in the long term. These environmental and production goals are defined so that they can be managed sustainably over time.

NOTE 1

For example, the use of special netting material that can resist the teeth of the predatory tiger fish, *Hydrocynus vittatus*.

Among ecological intensification systems, the one most heavily-researched and applied is undoubtedly IMTA (Integrated Multi Trophic Aquaculture).

In intensive aquaculture, large quantities of food are poured into the farms. This leads to the release of significant amounts of organic matter, either from the production of wastes by farmed animals or from the unconsumed food. The resulting pollution is harmful to the farmed animals themselves or to the environment (eutrophication).

With IMTA, wastes are recycled by one or several associated productions. For instance, intensive aquaculture produces nitrogen-containing waste that encourage the growth of aquatic plants. These plants are in turn consumed by herbivorous fishes.

Species used for intensive fish culture

Aquaculture production in sub-Saharan Africa essentially relies on two groups of native species – tilapias (187,625 tonnes in 2014, FAO statistics, 2015) and catfish (248,000 tonnes) – as well as introduced species, including carp (29,803 tonnes). Tilapias were used in the earliest aquaculture experiments in Africa, mainly in the Democratic Republic of the Congo and in Congo, primarily because they bred easily in captivity. Later, different species were tested to determine their aquaculture potential. In the Central African Republic in the early 1970s, the strong aquaculture potential of the catfish *Clarias gariepinus* was identified and extensive research was carried out on the species. In the 1980s, other species with good aquaculture potential were identified, notably in Côte d'Ivoire, based on their appeal to consumers and their zootechnical performance. The life cycle of some of these species has now been fully mastered, making it possible to start farming them.

Tilapia *s.l.*

Tilapia, which include the three genera *Oreochromis*, *Sarotherodon* and *Tilapia*, are without a doubt the most popular African species in terms of aquaculture. *Oreochromis niloticus* was one of the first to be cultured and remains the most common species (see box "Tilapia or 'aquatic chicken'"). Many other species have also been used: *O. andersonii*, *O. aureus, O. macrochir, O. mossambicus, Coptodon rendalli, T. guineensis, Sarotherodon melanotheron*. The latter, frequently found in West African estuarine and lagoonal systems, seems to be particularly suited to farming in brackish waters.

Clarias

The main culture species at present are *C. gariepinus* (by far the most widely cultured) and to a lesser degree, *C. anguillaris* and *C. ngamensis* in Africa, with a few others bred for the aquarium trade, most notably the Namibian endemic blind cave catfish, *C. cavernicola*.

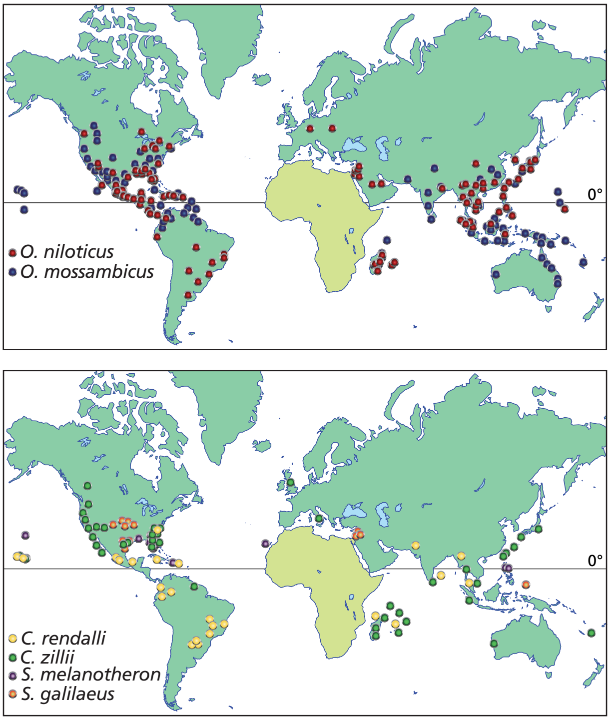
The only two members of the subgenus Clarias, *C. anguillaris* and *C. gariepinus* are very similar (Rognon *et al.*, 1998; Teugels, 1998; Teugels, 2003). Agnèse *et al.*

TILAPIA OR "AQUATIC CHICKEN"

Many of these species are now found throughout the world, either because they were introduced into natural systems to improve fisheries or because they were used for aquaculture (figure 26.1). Global aquaculture production of tilapia has increased considerably over the past ten years and was estimated at nearly 4,466,000 tonnes in 2014, 95% of which was *Oreochromis* (FAO statistics, 2015). Paradoxically, African fish farming only represents 5% (234,000 tonnes) of global tilapia production, even though these species are originally from Africa which hence represents the genetic reservoir for aquaculture carried out on other continents. The bulk of global production is currently in Asia (3,813,000 tonnes, *i.e.*, 85% of the global tilapia production).

FIGURE 26.1.

Introduction of tilapias s.l. outside Africa (data from GBIF, 2015).



(1997) found some evidence that *C. anguillaris* and *C. gariepinus* in the Senegal River hybridize naturally under certain conditions. Possibly due to the relatively restricted natural distribution of *C. anguillaris* in the Nile and West Africa, *C. gariepinus* is the more widely studied and cultured of the two.

Other indigenous species

One of the merits of determining which native species may be of interest for aquaculture is that it highlights neglected and unfamiliar species that have good aquaculture potential (Legendre, 1992; Lazard & Legendre, 1994).

In addition to the genus *Clarias*, there are three other Clariidae genera that are of at least some potential interest and have been tested in aquaculture. The endemic *Bathyclarias* species flock in Lake Malawi (ten or so species) ranges in size from 60-135 cm and has been tried in ponds in Malawi (Msiska *et al.*, 1991). *Gymnallabes typus*, native to the lower course and delta of the Niger River and Cross River basin in Nigeria and Cameroon has been tested as an alternative to eels in trials in the Netherlands (Teugels & Gourène, 1998).

Reaching over 1 m in length and 55 kg in weight (Skelton, 1993), the non-*Clarias* Clariid that has received the most attention from fish farmers and is actually produced in a number of African countries is *Heterobranchus longifilis*. Otémé *et al.* (1996) report that, under optimum conditions, *H. longifilis* grows twice as fast as *C. gariepinus*. This species is found throughout Africa in the Nile, Niger, Senegal, Congo, Gambia, Benue, Volta and Zambezi River systems as well as all the coastal basins from Guinea to Nigeria, and in Lakes Tanganyika, Edward and Chad.

Chrysischthys nigrodigitatus was also a promising catfish species, reaching more than 60 cm and extremely appreciated in many countries. Even though the farming cycle of this species has been fully mastered since the 1980s (Otémé *et al.*, 1996), its culture has never become widespread owing probably to the combination of several factors, including sexual maturity achieved only after 3 years at least, a relatively short reproductive season (only 3 or 4 months a year), and slow growth rate. It takes a year on average to obtain fish weighing 350 g. Nigeria had an annual production of 600 tonnes in 1993 (Coche, 1994). More recent studies no longer mention it (Ozigbo *et al.*, 2014)

The African bonytongue (*Heterotis niloticus*) presents many favourable characteristics for aquaculture, a remarkably high growth rate, air-breathing characteristic, omnivorous diet and a very good market potential. Fish exceeds 500 g within four months and a mean body mass of 3 up to 4 kg can be reached within a twelve-month cycle (Monentcham *et al.*, 2009). Despite that, production remains relatively low. It stood at 5,000 tonnes in 2013 (FAO statistics) of which 3,900 were produced in Nigeria.

Alien species

From the history of introductions and the development of successful aquaculture elsewhere, it appears that the use of exotic species to speed up the rate of aquaculture development in Africa is unlikely to be an efficacious strategy. The major sustained aquaculture industries worldwide evolved from close working relationships between pioneering investors and local research-and-development institutions. The use of indigenous species avoids many environmental risks, facilitates broodstock and hatchery management at the farm level, and can increase the effectiveness of selective breeding programs. Public-sector involvement in the domestication and marketing of indigenous species can strengthen research, development, and education; broaden the range of investors; create more jobs; and increase the social benefits accruing as a result of aquaculture development.

Despite the abundance and diversity of Cyprinidae in African inland waters, no indigenous species has been truly domesticated to date. There were however several attempts to introduce Asian cyprinids such as the common carp (*Cyprinus carpio*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*), and grass carp (*Ctenopharyngodon idella*). The common carp was thus first introduced in Madagascar then disseminated to about ten other countries including Kenya, Ethiopia, Cameroon, Malawi, Côte d'Ivoire, and Nigeria.

Control of reproduction

The supply of fry to fish farms still represents a bottleneck for many species of aquaculture interest that do not reproduce spontaneously in captivity. In the majority of cases, gonads develop normally in farmed fish, but final maturation of oocytes, ovulation, and spawning do not occur.

Collecting juveniles in the natural environment is an alternative that can help overcome this obstacle. However, this method has many disadvantages: inter-annual variability of catches, risk of mixing several species of unequal performance, and no possibility of genetic improvement. It is thus generally desirable, if not necessary, to do without natural resources and fully master the production of fry from captive breeders. This implies providing fish with the environmental stimuli needed for ovulation, or triggering the process using hormonal treatments.

Reproduction is controlled by the hypothalamic-pituitary-gonadal axis (Legendre & Jalabert, 1988; Goos & Richter, 1996). In species that achieve gonadal maturity but do not reproduce spontaneously in captivity, hormones needed for gametogenesis are produced in sufficient quantities. However, final maturation of oocytes, ovulation, and spawning do not take place because the peak in the release of gonadotropin (GTH) from the pituitary gland, needed to complete the process, does not occur. Downstream, at gonadal level, the release of gonadotropin that precedes ovulation triggers follicle cells to synthesize a steroid that induces oocyte maturation (17 α-hydroxy-20 β-dihydroprogesterone). Upstream, the release of gonadotropin by the pituitary is positively controlled by GnRH (Gonadotropin-Releasing Hormone) secreted by the hypothalamus and negatively controlled by dopamine. These hypothalamic controls are in turn dependent on environmental factors that are interpreted by the central nervous system.

In aquaculture, it is possible to trigger oocyte maturation and ovulation by intervening at different levels of this axis. This can be done by working on external factors and providing fishes with the stimuli needed for spawning (presence of specific spawning substrate, for instance) or by using various hormonal treatments. Depending on the species and methods used to trigger ovulation, eggs are obtained from either natural spawning or from gamete collection through abdominal massage of the breeders followed by artificial fertilization.

In *Clarias gariepinus*, which reproduces in the natural environment during the rainy season as waters rise, spawning in captivity can be triggered by simulating the flood. This is done by placing sexually mature breeders in a pool that is refilled after a drying-out period.

The use of hormonal induction techniques for oocyte maturation and ovulation, followed by artificial fertilization, are often preferred as they allow greater control of all the phases of reproduction and larval rearing (Legendre *et al.*, 1996). Moreover, they allow gamete conservation and various genetic manipulations, such as interspecies hybridization, gynogenesis, or polyploidy induction. These techniques nonetheless require the availability of qualified personnel and well-equipped hatcheries.

Sex control

Given that in Cichlidae, for example, males grow faster than females, it is advantageous to obtain monosex male populations that have better growth rates. This also offers the benefit of avoiding unwanted reproduction. Initially, selection was done manually after the appearance of the urogenital papilla, but this technique can only be used for fishes weighing around 20 to 50 grams. Moreover there is a non-negligible risk of error. A solution to limit the consequences of the latter is to associate a predator fish with the tilapia that will eat the fry that may be produced during the fattening phase. This combination of methods – manual sexing and predator-tilapia association – is deemed efficient and still remains in widest use in the context of artisanal African aquaculture, as it is the simplest to implement (Lazard, 1990b).

We can also consider hormonal sex inversion, and the masculinization of an alevin population by incorporating a synthetic steroid (17 a-methyltestosterone) in food (Baroiller & Jalabert, 1989). This method also offers the advantage of no longer requiring the elimination of the female half of juvenile stock, unlike manual sexing. The relatively empirical approach taken up to that point led rapidly to the adoption of masculinization treatments that are 100% effective, now used on a large scale in Asia. But questions have been raised regarding the fate of the breakdown products of the masculinizing hormone in animals intended for human consumption, as well as their potential ecological consequences. A possible solution lies in the use of natural hormones involved in the process of sexual differentiation, such as 11 b-hydroxy-androstenedione whose masculinizing efficiency has been demonstrated in *O. niloticus* (Baroiller & Toguyeni, 1996).

Genetic methods for sex control – gynogenesis, androgenesis, or interspecific hybridization – have also been used to produce monosex lines. Hybridization is presented later in this chapter. The principle of gynogenesis, in which only the female's genetic material participates in the development of the embryo, is as follows: oocytes are fertilized using irradiated spermatozoa. This does not prevent the spermatozoon from penetrating the egg cell and triggering its development, but destroys its DNA, thus eliminating any paternal genetic contribution. The normal diploid state of the embryo is then restored using chemical treatments or physical assaults (temperature, pressure) that block the first cell division. The principle of androgenesis is very similar, but in this case female genetic material is destroyed by irradiating oocytes. The two types of lines, gynogenetic and androgenetic, have been produced in *Clarias gariepinus* at the experimental scale (Volckaert *et al.*, 1994; Bongers *et al.*, 1995).

Food

In aquaculture systems, many investigations have studied the use of raw or compound feeds, formulated from agricultural and agro-industrial by-products available in tropical areas (Jauncey & Ross, 1982). Available data on the nutritional needs of African species remain limited and are especially focused on protein and energy requirements, and on the optimal protein/energy ratio in the rations. For tilapia juveniles, dietary protein requirements appear to be around 35% of raw protein regardless of species and dietary behaviour in the natural environment (Luquet, 1990). Among the Clariidae, optimal growth is obtained using feed containing 35 to 50% of raw protein. When taking into account the rations at which feed is distributed, this corresponds to an absolute requirement of 15 to 20 g of raw protein per kg of fish and per day, with a protein/energy ratio of 20 to 30 mg of protein per kJ of digestible energy (Wilson & Moreau, 1996).

In addition to the composition of dietary formulae, the different means of distribution of compound feeds (food ration, frequency, feeding period, food presentation) must also be taken into consideration as they can have a significant influence on nutritional efficiency and growth. For instance, in *H. longifilis*, the same dietary formula is used much more efficiently by the fish when it is distributed as pellets rather than in powder form (Kerdchuen, 1992). In this species, a very notable increase in growth is obtained when fishes are fed continuously rather than a series of meals. Feed distribution at night also yielded better results than when the fishes are fed by day (Kerdchuen & Legendre, 1991). Conversely, the tilapia *O. niloticus* is a diurnal species in which feeding essentially takes place during daytime (Toguyeni, 1996).

In some species, larvae do not yet have fully developed digestive tracts at the time of the first feed, and have specific behavioural and dietary requirements that are different from those of juveniles and adults. This is the case of *Clarias gariepinus* or *Heterobranchus longifilis* in particular. For these fishes, good growth and survival results have been obtained in hatcheries by feeding larvae with *Artemia* (a small crustacean) nauplii as their first food. But more independent resources must be sought in the context of many African countries where such prey must be imported. In this sense, the use of locally available zooplanktonic prey may address this need, whether they are produced in associated farms or used *in situ* in fishponds. To be effective, the latter method would require the use of fine-meshed cages to protect larvae from predators, and extensive knowledge and good control of the pond ecosystem (Legendre, 1992). Recently, progress has been made in identifying artificial feeds adapted to the specific dietary needs of larvae. The use of a compound feed based on yeasts and beef liver thus made it possible to achieve a high survival rate in *H. longifilis* (Kerdchuen, 1992 ; Kerdchuen & Legendre, 1994). But growth is still inferior to that attained with *Artemia* or zooplankton, indicating that the dietary needs are still not fully covered.

Fish farming structures

Aquaculture is highly flexible and adaptable to a wide range of environments, markets and investment levels from small ponds that produce a few kg of fish for home consumption up to high density raceways or cages that can carry hundreds of kg per m^3.

Ponds are the cheapest and simplest systems to build and manage, the main problem being that they must be sited in areas where the soil is heavy enough to hold water and the topography has enough slope to permit complete draining without the use of expensive pumping.**2** Ponds also take up a lot of space as their carrying capacity seldom reaches 1 kg per m^2, being limited by the ability of the natural ecosystem to produce oxygen and absorb metabolic wastes. On the other hand, fish growing in the more or less natural environment of ponds are at relatively reduced risk of stress and disease and if properly fed can grow efficiently on a combination of low-value inputs and natural foods.

NOTE 2

Depending upon land value and/or water supply it can be cost-effective to use plastic liners in areas where pond construction would otherwise be impossible.

Raceways are round or elongate, usually built of cement with water flow-through or recirculation through a biofilter to add/replace oxygen and remove metabolic wastes. Raceways take up less space than ponds, are easy to harvest and can carry as much as 100 kg/m^3 of *O. niloticus* (Watanabe *et al.*, 2002; Ridha *et al.*, 2001) or 400 kg per m^3 of *C. gariepinus* (Hecht *et al.*, 1996). However, they are expensive to build and require electricity and/or a high volume of water, although most of the water is of good quality at the outfall and can be used for other purposes. Because there are no natural foods in raceways, the fish must be fed a complete diet. In addition, the artificial environment creates the potential for disease and mechanical damage to fish living in cramped quarters.

Recirculating systems are normally based on raceway technology with a filtration system installed to remove nitrogenous wastes, add oxygen and cycle the water back to the fish. These systems are very popular in areas close to big cities where land and water are scarce and expensive. They are, however, complicated and expensive to build and operate and even short electricity failures can result in disaster. Also, being unnatural environments, the fish face the same constraints as in raceways, including the need for a complete diet.

Most of these problems have been overcome in the SARI system (Système Aquacole à Recyclage Intégral: Fish Farming System with Complete Recycling). This recirculating system has been first dedicated to the black chinned tilapia *S. melanotheron* kept in brackish water. Fish excrements fertilize water and help the phytoplankton to grow (green algae). Zooplankton feed on this phytoplankton and is, in turn, eaten by juveniles of *S. melanotheron*. This system saves 2/3 of aliment incomes, 9/10 of usual water intake, and produces no waste water. A prototype build in 2013 was still functioning in 2015 (figure 26.2).

Cages come in many shapes and sizes depending upon the availability of materials, the type of water body into which they are installed, and the amount of money available to invest. The number of cages that can be installed in any given water body depends upon depth, water current, and wind velocity, all of which contribute to the circulation of water through the cage. Fish in cages lack access to most natural foods, so production depends upon the provision of a complete pelleted diet. Cages are easy to harvest and are modular so that the system can be scaled up as the farmer gains experience and the market grows.

In smaller water bodies, cages have a big advantage over capture fisheries in terms of resource utilization. Instead of having a mixed flock of different species and ages, caged fish are all in one place so they can be easily fed and

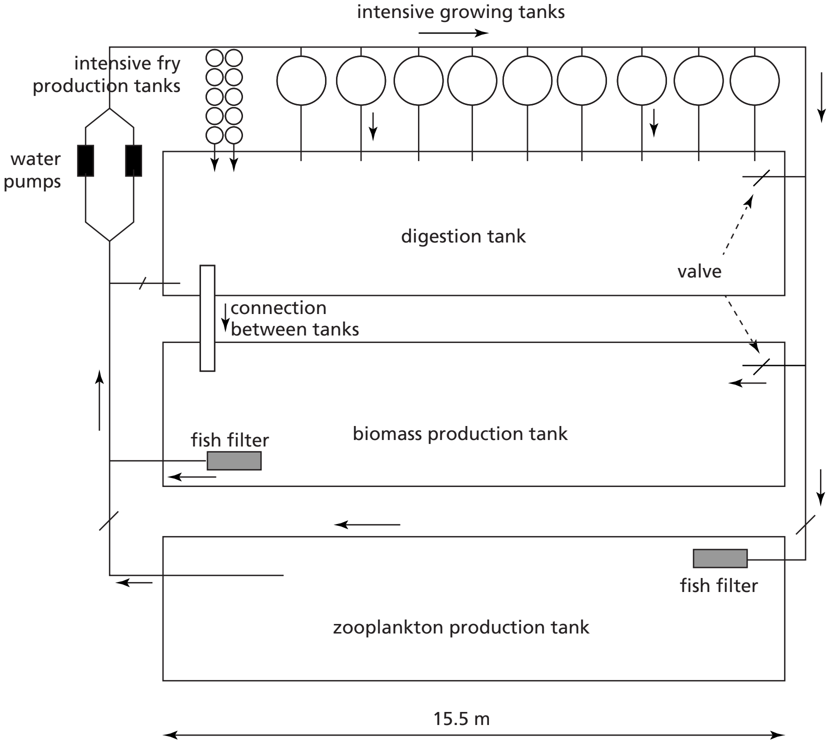


FIGURE 26.2.
The SARI prototype plan. The digestion tank ensures the complete degradation of organic effluent; the biomass production tank is dedicated for continuous supply of phytoplankton; the zooplankton production tank operates as regulator of phytoplankton biomass and for production of zooplankton biomass (from Gilles & Blancheton, 2010).

managed. The highest natural productivity of small water bodies is no more than 300 kg/ha. The same water body used for fed cages would be at least 3 tonnes per hectare.

All food production systems require water and conflicts over access to increasingly scarce resources are creating conflict in almost all African countries. Although plants provide more food per litre of water than animals, animals provide higher quality protein. Among animals, fish are by far the most efficient energy users. Channel catfish (*Ictalurus punctatus*), for example, gain 0.85 g of weight for every gram of feed consumed, compared to 0.48 g in chickens, the most efficient warm-blooded animal, and 0.13 in beef cattle (Lovell, 1989). Fish production, being conducted entirely underwater, would seem to be potentially one of the greater water consumers. However, consumptive use of water by aquaculture is, in theory, negligible. Also, aquaculture has the advantage over rain-fed plant crops by being somewhat disconnected from rainfall periodicity. Through the use of recirculation technology and/or integration of cage aquaculture into other water use schemes, consumptive use of water can be reduced even further to the amount lost to evaporation and leakage, which in water-stressed areas are often controlled with the use of plastic liners and/or greenhouse-like covers.

Tilapia culture in ponds is growing rapidly and typically produces standing crops of 5-6 tonnes per hectare with a consumptive water use of about 2,800 l/kg of fish produced, including the amount needed for feed production[3] (Brummett, 1997), less than the 3,500 l/kg required for broiler chickens (Piemental *et al.*, 1997). Lazard (2002) reported production of up to 15 tonnes/ha/y of tilapia in static water ponds in Côte d'Ivoire. In South Africa, pond-based flow-through systems can produce *C. gariepinus* standing stocks of up to 40 tonnes/ha/8 months with a water exchange rate of 2-6 l/sec/ha, equivalent to 3,600 l/kg. Overall, commercial freshwater aquaculture probably uses something on the order of 5,000 l of water per kg of fish produced, although most of this use is non-consumptive, being either directly usable for other purposes or indirectly usable following settling or biofiltration to remove excessive nutrients and/or suspended solids.

NOTE 3

[3] Producing the feed used by commercial fish growers requires approximately 1.54 million liters of water to produce 1 tonne of fish food, containing 48% soybean meal and 41% corn meal (Lovell, 1989).

Genetic manipulations and fish culture

Selecting high-performance genotypes

In aquaculture, the goal is to produce fish of a tradable size as quickly as possible. To do so, there has been an attempt to select the most efficient strains, and one of the possible ways is through genetic improvement which consists of replacing a population composed of certain genotypes by other genotypes that perform better in an aquaculture setting. Such selection programmes have been carried out successfully for temperate species such as trout, but are still in preliminary stages for African species. That said, a number of tilapia farms are beginning to apply the principles of quantitative genetics. The GIFT (Genetic Improvement of Farmed Tilapia) programme conducted by ICLARM, for instance, consists of collecting different tilapia strains and evaluating their growth characteristics in different environments (see box "The GIFT Tilapia").

There have also been attempts to modify species performance artificially by trying to obtain advantageous characteristics through the production of hybrids or other genetic manipulations such as polyploidy induction.

Polyploidy is a condition in which individuals have extra sets of chromosomes. An individual normally possesses two sets of chromosomes in its cells and is referred to as diploid. Triploidy affects individuals with 3 sets of chromosomes; those with 4 sets are called tetraploid. These two situations can be obtained in fish by subjecting fertilized eggs to thermal shock or high pressure, or by chemical treatment. Triploid individuals are sterile and, in theory, the energy absorbed through food, which would not be used for gonadal development or reproduction, would instead be available for greater somatic growth. Moreover, the nuclei of polyploid cells are bigger than those of diploid cells and, in some species, the cell's cytoplasmic volume increases proportionally. In some cases this therefore results in larger cells and an overall increase in body size. In *Clarias gariepinus*, triploids have been obtained by subjecting eggs to cold shocks (Henken *et al.*, 1987). No difference in growth or efficiency in nutrient use was observed between diploid and triploid *Clarias,* but the amount of flesh remaining after evisceration was noticeably greater.

THE GIFT TILAPIA

The GIFT Tilapia was selected in the Philippines in 1988 by ICLARM (the International Center for Living Aquatic Resources Management), now the WorldFish Center, the BFAR (Philippines Bureau of Fisheries and Aquatic Resources, the FAC-CLSU (Freshwater Aquaculture Center of the Central Luzon State University, the UPMSI (Marine Science Institute of the University of the Philippines), and the Institute of Aquaculture Research, Ltd., in Norway (Ansah *et al.*, 2014).

Wild Nile tilapia germplasm from Egypt, (Nile Delta), Ghana (Volta), Senegal (Senegal) and Kenya (Lake Turkana) were collected together with four commercial Nile tilapia strains from the Philippines (three strains originated from Ghana, and one stock originated from Egypt).

The best-performing purebred and crossbred groups were selected, based on their growth performance, in order to build a stock with a broad genetic base. This constituted the original GIFT strain on which selective programs have been applied.

Rapidly the GIFT strain resulted in body weight up to 58% higher than "non-GIFT" strains on "average" farms in Asia where it has been disseminated (Bangladesh, People's Republic of China, Philippines, Thailand, and Vietnam).

In 1999, a Norwegian company got an exclusive agreement for the long-term continuation of the GIFT breeding programme. DNA marker-assisted selection has been applied in order to increase the selection differential that resulted in gains of 10%-15% per generation over more than six generations.

The outcome of the GIFT project generated interest from developing countries not only in Asia but also in Africa.

An expert consultation in 2002 in Nairobi confirmed the policy of the WorldFish Center not to introduce the GIFT strain into countries where *O. niloticus* is indigenous, mainly because interbreeding of the GIFT strain with locally-adapted native populations might compromise wild aquatic genetic diversity.

Instead, the WorldFish Center decided to help African countries to apply the GIFT methodology to the genetic improvement of indigenous tilapias in Cote d'Ivoire, Egypt, Ghana and Malawi.

But it is quite a paradox that the African continent whence originated tilapia benefits the least from the GIFT strain, even though much of the continent has a high potential for tilapia farming.

Finally, after growing pressure for the dissemination of the actual GIFT germplasm to Africa, the WorldFish Center approved the Policy on the Transfer of GIFT from Asia to Africa in 2007.

GenoMar also supplied the genetically improved strain to hatcheries in Zambia, Angola, and Uganda. The Ghana Aquaculture Research and Development Center (ARDEC) received the GIFT strain in 2012, with the expressed objective of comparing its growth performance.

It is now clear the GIFT tilapia will expand its range all over Africa, even if some countries like Ghana prohibited the culture of this strain because the environmental risk assessment has not been completed yet.

The crossing of neighbouring species can produce hybrid individuals possessing characteristics that are sought after in farmed animals: sterility, monosex lines, improved disease resistance or growth compared with parents, combinations of biological traits that were present separately in the parents, among others. The performances of hybrids are nonetheless hard to predict from the outset and must be tested experimentally.

It has thus been noted in tilapia that the crossing of certain *Oreochromis* species led to the production of hybrids that were all male (Wolfarth & Hulata, 1981). These hybrids were interesting as they provided male tilapia, which grew faster than female tilapia, and also prevented unwanted reproduction in fish farms. In practice, however, it turned out to be very difficult to maintain this production of very high percentages of males through hybridization, in particular due to contamination of parental strains of progenitors by hybrid descendants (phenomenon of introgression). At present, the use of these hybrids has yielded to other methods of sex control that are more efficient and easier to implement, such as hormonal inversion.

Genetic diversity in cultured stocks

Romana-Eguia *et al.* (2005) observed a strong loss of genetic variation in selected lines for size specific mass selection in the tilapia *O. niloticus*. The degree of inbreeding within the selected lines was higher (107.9%) than the control line (64.2%) after four generations. While changes in genetic diversity arose as expected in the selected lines because of artificial selection, genetic variabilities in the control lines was unexpectedely lowered by genetic drift and by unconscious selection. Looking specifically at the GIFT strain of Nile tilapia (*Oreochromis niloticus*), Ponzoni *et al.* (2010) observed that the rate of inbreeding was 0.0037 per generation and the effective population size was 88. They concluded that the mate allocation strategy has been successful in containing inbreeding and that the effective population size is satisfactory for the sustainability of the selection program. Fry production in *Oreochromis niloticus* is often achieved by mass spawning of males and females stocked in ponds. Fessehaye *et al.* (2006a) demonstrated that territorial behavior and reproductive competition among males may lead to a large variance in reproductive success among individual males, leading to one-third of males siring more than 70% of the offspring. The rate of inbreeding could be about twice the inbreeding expected in an idealized population of the same census size. While Fessehaye *et al.* (2006b) observed that the level of inbreeding did not affect survival and body weight at harvest in *O. niloticus*, Vitalaru *et al.* (2014) concluded that inbreeding can lead to morphological abnormalities. Substantial declines in performance are associated with usual hatchery management practices (Brummett, 2013). Genetic variability of fish held in African hatcheries is 40-70% less and growth rates 12-40% less than wild stocks (Eknath *et al.,* 1993; Morissens *et al.,* 1996; Pouyaud & Agnèse, 1996; Brummett *et al.,* 2004).

As with Tilapia species, domestication or captive *Clarias* breeding has resulted in a certain amount of genetic change, usually deterioration. Da Costa (1998) found a 20% difference between cultured and wild stocks of *C. anguillaris*, with the cultured stock performing significantly worse. Otémé (1998) and Agnèse *et al.* (1995) found that a population of *H. longifilis* held for four generations on a government research station had reduced genetic variability, lower fry growth rate and survival, higher levels of fry deformity and greater variability in larval growth rate. Van der Bank (1998) found that mean heterozygosity in a captive population (0.3%) of *C. gariepinus* was an order of magnitude less than in a wild population (5%). Hoffman *et al.* (1995) found that wild *C. gariepinus* grew 15-43% better under culture conditions than populations that had been held on-farm. Van der Walt *et al.* (1993a) reviewed genetic variability in *C. gariepinus* and found strong evidence of inbreeding, founder effects and genetic drift in most captive populations.

Good genetic management can reverse many of these negative consequences of domestication and even improve performance. Van der Bank *et al.* (1992) and Grobler *et al.* (1992) showed that out-crossing to other captive stocks and with wild fish raised mean heterozygosity of a farmed population to 7.6% compared to 5% in a wild stock. Similarly, Teugels *et al.* (1992) found that populations of *C. gariepinus* that were purposefully out-crossed among research stations were significantly more heterozygous than fish held in isolation on a single station. Among *C. gariepinus* stocks, significant variation in growth indicates that selection for better performance in aquaculture is possible (Van der Bank 1998). Van der Walt *et al.* (1993b) showed that a well-maintained experimental line of *C. gariepinus* outperformed wild strains and a population held on a local hatchery. Martins *et al.* (2005) documented significant variation in growth among juvenile *C. gariepinus*, implying that selection is possible.

Conservation status

Most members of the genus *Clarias* are under no particular danger of extinction at the present time. Four species, all African, appear on the IUCN Red List of Threatened Species (2007): *C. alluaudi, C. cavernicola, C. maclerni* and *C. werneri*. The closely related, and easily confused, *C. alluaudi* and *C. werneri* (Seegers, 1996) are considered as of Least Concern, with widespread distributions and no particular threats. *C. cavernicola* and *C. maclerni*, on the other hand are considered as Critically Endangered. *C. cavernicola* is endangered due to the fact that its entire range is a single 45 m^2 pool in the Aigamas cave, Namibia and the water level is going down due to groundwater extraction in the area. *C. maclareni*, while under no specific threat, occupies one small lake, Barombi Mbo (diameter of 2 km).

Although *Clarias* species are generally quite hardy, Mohamed *et al.* (1999) found that a section of the Nile River which received heavy levels of industrial pollution contained significantly fewer *C. gariepinus* than other sections and attributed this to poor water quality. As they are originally best adapted to swampforest habitats, *Clarias* species worldwide have come under increasing pressure as forests become increasingly fragmented (Sudarto, 2007).

Interactions between farmed lines of *Clarias* and wild populations may represent a significant threat to the genetic integrity of the latter. There appears to be a significant amount of genetic differentiation across the distribution of *C. gariepinus*, with populations in West/Central Africa differing morphometrically (width of pre-maxillary toothplate, length of occipital process, and dorsal fin length) from those in Eastern and Southern Africa (Teugels, 1998), possibly reflected in earlier taxonomic recognition of three species, two of which – *C. mossambicus* and *C. gariepinus* – have since been incorporated into *C. gariepinus*. Transcontinental movement of populations used for aquaculture may pose a threat to this differentiation.

In Africa, the *H. longifilis* x *C. gariepinus* hybrid, once thought to be sterile, has been recently shown to have the capacity to interbreed with wild *C. gariepinus*, creating what is effectively a transgenic Clariid, with unpredictable consequences for the wild populations, but quite possibly including a reduction in overall fecundity and therefore fitness leading to reductions in the wild stock

(T. Hecht, personal communication, 2005). Euzet & Pariselle (1996) found that "heteroclarias" juveniles were susceptible to *Henneguya* infections to which both pure *Heterobranchus* and *Clarias* were immune, raising further questions about the wisdom of creating this hybrid.

In addition to the dangers posed to indigenous biodiversity by these inter-specific and inter-generic hybrids, concerns have been expressed about the possible negative consequences of escapees from monogenetic but domesticated culture populations reducing the fitness of conspecific wild populations. The magnitude of this threat is proportional to the genetic distance between wild and captive populations. If the difference is extreme, introgression of domesticated genomes into what is theoretically defined as a perfectly fit wild population unavoidably reduces the purity of the wild genome. Whether such a change in gene frequencies represents a real threat to survival is unknown. Both in the wild and in captivity, shifting gene frequencies are a natural consequence of any significant change in the environment. In cases where important or rare *Clarias* biodiversity may come under such a threat, every effort should be made to assess the actual risks prior to introducing cultured populations to a new area.

Most of the Tilapia species like *Clarias* cannot be considered as ciritically endangered but some of them are threatened like *O. esculentus* and *O. variabilis* in the Lake Victoria basin, *O. karongae* and *O. idole* in the Lake Malawi drainage (IUCN Red List of Threatened Species (2007)). If there is no critically endangered species, some populations can be considered as seriously threatened, especially in species important for aquaculture like *O. niloticus* and *O. mossambicus*. For example, the newly discovered natural population from the Loboi swamp (Nyingi *et al.*, 2008) seems to be restricted to a few-hundred-metre-small hot stream ending into a swamp connected with the Lake Baringo drainage. The swamp, mainly composed of papyrus, is acting as a biological barrier that keeps fish from moving from the lake to the stream or vice versa.

Today, these populations are threatened due to environmental instability and anthropogenic activities within the region. The macrophytes within the swamp have been receding significantly due to encroachment of the swamp for agriculture and harvest of papyrus for roofing and other uses. The swamp itself has been reduced by at least 60% in the last 30 years due to irrigation activities (Harper, 2003). Finally, one other great danger to this unique genetic resource of the Nile tilapia is the recent growth of aquaculture development in the region. Fish from other basins are currently being introduced for culture in ponds closely associated to streams of the region. Escapees from these ponds would certainly pollute the genetic integrity of the natural populations of the Nile tilapia

This is exactly what happened in Lake Baringo that hosts one of the *O. niloticus* subspecies, *O. n. baringoensis*. Haplotypes of this subspecies were found to be introgressed with those of *O. leucostictus*, a species endemic to Lake Albert in Uganda but introduced into Lake Naivasha, which neighbours Lake Baringo (Nyingi *et al.*, 2007). This introgression was initially thought to be unaccompanied by any detectable transfer of nuclear DNA. Specimens of *O. leucostictus* were suspected of having been introduced into Lake Baringo for the purpose of improvement of tilapia stocks. They may however have escaped from aquaculture activities in the region. In a second study, Ndiwa *et al.* (2014) demonstrated that not only was there a notable amount of nuclear gene transfer, but that this introgression also occurred in adjacent natural population of *O. niloticus* from Lake Bogoria hotsprings in the Loboi River drainage. It is very likely that the recent intensification of aquaculture activities in this drainage may be responsible for these introgressions.

This tilapia is not the only one to be introgressed. D'Amato *et al.* (2006) observed many introgression cases in the Mozambique tilapia (*Oreochromis mossambicus*) in its native range, southern Africa. Hybridization of *O. mossambicus* was indicated by the presence of *O. niloticus* and *O. mortimeri–andersonii* mtDNA specimens in the Limpopo basin and of *O. karongae* mtDNA in specimens from Malawi.

So far it is clear that tilapia are prone to hybridizing quite easily with closely related species occurring naturally or introduced due to human interventions. In Africa, the most important culture species are still mainly taken from the wild and populations are often taken to a different basin far beyond their natural range, thus interrupting the natural allopatry with related species and populations. The complex nature of hybridization and introgression between cichlid species raises major concerns for the long-term integrity of tilapia species. Paradoxically, fish culture activities could represent a major threat for aquaculture natural resources, resulting in the rapid decline or total disappearance of the native populations.

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The Inland Water Fishes of Africa

Diversity, Ecology and Human Use

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