GIFT transfer risk management: Ecology

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Executive summary

The selectively bred strain known as Genetically Improved Farmed Tilapia (GIFT) was the outcome of efforts to develop a fish variety of high aquaculture performance. Not genetically modified or transgenic, this new variety was bred using traditional selective breeding methods through a carefully conducted genetic selection and improvement program. The program was based on broodfish collected from four African countries and four commercial Nile tilapia (*Oreochromis niloticus*) strains used in the Philippines.

Initially, it was WorldFish policy not to introduce the GIFT strain into African countries where Nile tilapia is indigenous. The concern was that interbreeding of the GIFT strain with locally adapted native populations might compromise wild aquatic genetic diversity. However, WorldFish has subsequently changed its policy and approved the transfer of GIFT from Asia to Africa. The strain is now available to any African government that can demonstrate procedures to manage environmental and biodiversity risks, among other conditions. In response to a request from the government of Nigeria for the transfer of GIFT, WorldFish plans to invest in a research and development (R&D) program that provides the foundation for establishing a sustainable private sector-based GIFT seed and grow-out industry in Nigeria.

The plan is to transfer a batch of GIFT from Malaysia to Nigeria around July 2021. The fry will be produced at WorldFish's GIFT broodstock facility in Penang, Malaysia, using 17th generation GIFT as parents. The transferred fry will be kept in a designated land-based, secured quarantine facility in Nigeria's Ogun State and will be raised with regular health checks. G2 progeny resulting from the originally transferred stock (G0) will be transferred to Delta State for breeding (non-sex reversed fry weighing 10 g) and for grow-out (sex reversed all male fry weighing 2 g). G2 fish will be cultured in both land-based and water-based systems (ponds and cages) in the two states. Nigeria's freshwater habitats are suitable for the growth and propagation of Nile tilapia, and it is a native species in Nigeria and beyond.

The ecological and environmental risk analysis of the proposed transfer from Malaysia to Nigeria is based on the guidelines given in the International Council for the Exploration of the Sea's Code of Practice for the Introductions and Transfers of Marine Organisms (ICES Code). This risk analysis is exclusively based on information gleaned from published research articles and reports on the status of tilapia in Asia, Africa and other geographical regions, including their ecology, invasive status, aquaculture performance, environmental and socioeconomic impacts. Furthermore, in risk analysis, there is a wealth of information that was also reviewed regarding possible implications of introducing GIFT into some countries in Asia. Accordingly, the ecological and environmental risk analysis was summarized under 11 risk assessment framework considerations as follows:

1. Invasive success of the non-native GIFT in the recipient country

In many countries, introduced Nile tilapia is considered as an invasive species. Nevertheless, tilapia introductions often represent a trade-off between resulting positive and negative ecosystem services. In some Asian countries, GIFT adoption increased both tilapia and total fish production, enhanced profitability of fish farming, lowered tilapia prices, increased consumption of tilapia and other fish among consumers and GIFT farmers, and improved the economies. Characteristics of GIFT such as surface feeding on pelletized food and its inability to compete with wild stocks for natural food may not be beneficial for it to perform in the wild. It is therefore unlikely that any GIFT that escape from aquaculture systems would get established in the wild.

2. Convention on Biological Diversity requirement of the recipient country

The Convention on Biological Diversity (CBD) requires the recipient country to prevent the introduction, control or eradication of alien species that threaten the ecosystems, habitats or species. The development objectives that Nigeria intends to achieve with the GIFT introduction include improving nutrition in rural areas, generating supplementary income, diversifying income activities and creating employment. It is recommended that an independent national advisory team identify water bodies in Nigeria where the use of GIFT should be restricted or prevented to avoid ecological and environmental risks.

3. Balancing ecological risks and economic gains
Measures to address possible adverse impacts of species introductions in inland waters should be undertaken through science-based risk assessments. It is believed that, as in Asia, substantial improvements in aquaculture production in Africa can be achieved through GIFT aquaculture.

4. Potential to alleviate food insecurity, malnutrition and poverty
There is considerable motivation to develop aquaculture in sub-Saharan Africa, including small-scale cage farming in the region's large lakes as well as small-scale fish farming integrated into family agriculture systems.

5. Sharing benefits of GIFT R&D with African countries
As Africa supplied Nile tilapia genes to develop GIFT, it is legitimate to share the benefits of GIFT R&D with African countries.

6. Changing anti-tilapia attitudes
To sustain tilapia aquaculture in Nigeria, it is necessary that anti-tilapia attitudes are changed and that environmentally compatible enterprises are introduced that are well-integrated with other development initiatives.

7. Better practices for tilapia faming and husbandry
Good husbandry and environmentally friendly farming practices are essential for minimizing adverse environmental effects from tilapia farming.

8. Potential environmental risks associated with biosafety
Introducing GIFT into Nigeria should be coupled with forming and implementing appropriate policies, rules and regulations for environmental safeguards.

9. Habitats
Nigeria has more than 260 medium and large dams, with a combined storage capacity of more than 30 billion m^3 of water. The dams can be used for cage and pen aquaculture.

10. The presence of natural enemies, predators and competitors
There are several species in Nigeria that are used for population control of Nile tilapia aquaculture ponds. They can be considered potential predators of GIFT. In Lake Victoria, Nile tilapia co-exists with Nile perch (*Lates niloticus*), so the presence of predators does not appear to be a major issue for GIFT introduction.

11. The presence of potentially reproductive compatible species
There are over 25 species of tilapia in Nigeria. Of these, *Oreochromis aureus* is the only native species in the country and is a potentially reproductive compatible species with Nile tilapia.

Accordingly, the following ecological and environmental risk management measures are recommended to be implemented:

Before transfer

1. Appropriate policies, rules and regulations and implementation mechanisms should be in place for aquaculture development with long-term biosafety, quarantine and other environmental safeguards.
2. An independent national advisory team should identify water bodies in Nigeria where the use of GIFT should be restricted or prevented to avoid ecological and environmental risks.

During transfer

1. Regular health checks should be supplemented with occasional assessment of genetic resources to ensure genetic diversity is not being lost in subsequent generations.

2. Best aquaculture practices should be adopted with strong measures to prevent farmed fish from escaping, and monitoring the surrounding environment for GIFT is essential.
3. Capacity building and awareness creation activities for key stakeholders are necessary to reduce the risk of illegal transfer of GIFT and to increase awareness of GIFT in Nigeria.

After transfer

1. WorldFish's follow-up activity for introducing GIFT should be implemented to ensure long-term effectiveness of the breeding programs.
2. GIFT fish farming should follow more effective preventive measures to avoid the release or accidental escape of cultivated individuals at all fish farming stages. Potential adverse environmental effects from farming GIFT in Nigeria should be minimized through good husbandry practices.

Photo credit: Trong Quoc Trinh/WorldFish

Harvesting GIFT (Malaysia).

Terms of reference

Component I

The ecological and environmental risk management plan will achieve the following:

- Examine and review the information provided by WorldFish on the ecological and environmental aspects associated with the proposed transfer of GIFT from Malaysia to Nigeria.
- Conduct, with the assistance of WorldFish (if requested), a detailed review of the relevant literature dealing with the ecological and environmental impacts of previous transfers of Nile tilapia.
- Follow current best practices, which may include the general methods outlined in the Food and Agriculture Organization's (FAO) Fisheries and Aquaculture Technical Paper No. 519 and the guidelines given in the ICES Code.
- Assess both direct and indirect ecological and environmental risks to the potential receiving environment.
- Supply a document that provides an assessment of the ecological and environmental risks associated with the proposed transfer and also outlines a risk management plan, including recommended risk management measures, that could be implemented before, during and after transferring GIFT from Malaysia to Nigeria.

Component II

Procedure for doing a literature search on tilapia disease, pathogens and mortalities in Africa and Asia:

1. List (tabulate) all citations, including title, year and author/s.
2. Include the abstract under each citation.
3. If PDFs are available, save them in a file.
4. Repeat the same for genetics and ecology.
5. For genetics, use these keywords: (a) tilapia + genetics/genetic improvements/introductions/transfers/genetic risks/genetic impacts in Africa and Asia.
6. For ecology, use these keywords (among others): tilapia + impacts of introduction, ecological impacts, ecological risks, escapees, etc.

Taxonomic note

The valid scientific names of fish species as listed on www.fishbase.org are used in this document.

1. Introduction

The introduction of species across biogeographic barriers by human activities is widespread, causing global biodiversity loss and subsequent environmental change. It is undisputedly accepted that managing an introduction of a non-indigenous species into a particular geographical region should be based on a precautionary approach (Bailey et al. 2020). According to the FAO Database of Introduced Aquatic Species,[1] the reasons for introduction are predominantly for aquaculture (39%), fisheries (17%), ornamental and accidental (8%), biocontrol (6%) and, interestingly, for "other" and "unknown" reasons (22%). Undoubtedly, this evidence suggests that aquaculture has driven a great bulk of introductions of alien aquatic species (Cuvin-Aralar 2016). The growth of the human population poses significant challenges to the supply of high-quality, nutrient-rich food for a worldwide population that is projected to reach 9.7 billion by 2050, requiring an increase in the food supply by 25%–70% (Hunter et al. 2017). For this reason, many attempts have been made to improve the efficiency of food production systems. This includes exploring considerable scope for improved efficiency in fed aquaculture and discussing the development and optimization of alternative protein sources for aquafeeds to ensure a socially and environmentally sustainable future for the aquaculture industry (Hua et al. 2019). It also includes a move to improve the environmental performance of aquaculture by developing systems such as "multi-trophic aquaculture" in which low-trophic-level species use the nutrient-rich by-products of high-trophic-level species (AFD/EC/GIZ 2017). The selectively bred strain that came to be known as GIFT was the outcome of efforts to develop a variety of high aquaculture performance. The genetic gain per generation in GIFT was about 17% across five generations of selection for growth, and the accumulated genetic gain in relation to the base population was 85% (Ponzoni 2008).

1.1. Background

Tilapia is one of the most important groups of aquaculture species in the world. In 2018, of the 82.1 million metric tons of aquaculture food-fish production, 5.5 million metric tons came from tilapia (FAO 2020), 81% of which was Nile tilapia (FAO 2020).

Fish is critically important to Nigeria for food and nutritional security, foreign exchange, employment and livelihoods. Yet, a steep change in supplies and distribution is necessary over the next 20 years to realize its full potential. As the country's population increases from 196 million in 2018 to 263 million in 2030, an additional supply of 752,000 t of fish will be needed to maintain the current level of national per capita fish consumption (11.2 kg), and 3.14 million metric tons will be needed worldwide to reach the current level global per capita fish consumption (20.3 kg) by 2030. This market situation provides significant new opportunities for aquaculture growth, creating opportunities for smallholders, jobs along the value chain, women's empowerment and nutritional improvement.

In Nigeria, main bottleneck to expanding tilapia aquaculture and production (including through smallholder-based farming) is the lack of a systematically managed and maintained breeding population to produce high-quality seed in required quantities that are accessible to farmers year-round. Recognizing the importance of using an improved variety of tilapia to support the necessary growth of the tilapia sector, the Honorable Minister of Agriculture and Rural Development in Nigeria recently made an official request to WorldFish to transfer GIFT from Malaysia to Nigeria and to assist in creating a GIFT seed industry in the country.

Several studies have identified socioeconomic benefits arising from farming GIFT, including improved rural income and employment (Yuan et al. 2000; Dey and Gupta 2000; Gupta and Acosta 2004; Trong et al. 2021). According to the Asian Development Bank (ADB) (2005), "the economic internal rate of return on investments in GIFT development and dissemination was more than 70% over a period from 1988 to 2010, with an estimated net present value of US$ 368 million in constant 2001 prices." It has been estimated that nearly 50% of global Nile tilapia aquaculture production is now GIFT and GIFT-derived. About 75% of tilapia consumed in developing countries appear to be GIFT, confirming that the strain has the greatest potential for alleviating global poverty and hunger and for improving nutrition.

In general, tilapia is a food commodity with a low carbon footprint in terms of greenhouse gas emissions that can improve the resilience of both small-scale farms and the overall food system. WorldFish believes that transferring GIFT would kickstart a new domestic industry in Nigeria for tilapia production. It would increase smallholder income and employment, deliver significant quantities of new fish products to narrow the fish supply-demand gap, and lead to better nutrition and health among the Nigerian population. Smallholder GIFT farming would create an industry that will increase the availability of a low carbon food commodity in Nigerian markets.

1.2. Genetically Improved Farmed Tilapia (GIFT)

Nile tilapia is a cichlid fish native to the northern half of Africa and Israel, and numerous introduced populations exist outside its natural range. Several genetic improvement programs have been developed for Nile tilapia (Komen and Trong 2014). These include the GIFT project developed in the 1980s by WorldFish, then known as the International Centre for Living Aquatic Resources Management (ICLARM). GIFT is the first genetically improved tropical aquaculture fish species in the world. Neither genetically modified nor transgenic, this new species was bred using traditional selective breeding methods to produce a "super" tilapia. This strain of Nile tilapia is a product of over 30 years of selective breeding by WorldFish and its partners in Norway and the Philippines, using the same selective breeding method used in Norway in the 1970s for salmon and trout. GIFT was developed under the framework of a project that aimed to increase the efficiency of tilapia aquaculture efforts. Spearheaded by ICLARM, the United Nations Development Program (UNDP) and the ADB, GIFT is derived from eight natural and farmed stocks of Nile tilapia (Dey et. al. 2000).

Over the years, GIFT has officially been introduced or transferred to 11 countries in the world for experimental or dissemination purposes: Bangladesh, Brazil, India, Indonesia, Fiji, Malaysia, Myanmar, Philippines, Thailand, Timor-Leste and Vietnam. There are also records of unofficial movement or transfer of GIFT to many other countries, including Nigeria.

1.3. Nature of the plan

WorldFish has received a request from the Government of Nigeria for the transfer of GIFT. In partnership with Bill & Melinda Gates Foundation (BMGF) and the United States Agency for International Development (USAID), WorldFish plans to invest in a R&D program that will provide the foundation for establishing a sustainable private sector-based GIFT seed and grow-out industry in Nigeria. This program is designed to (a) prepare and biosecurely transfer GIFT from Malaysia to Nigeria, (b) establish a GIFT breeding population for disease-free broodstock/seed dissemination, and (c) establish a healthy GIFT seed industry/business and GIFT-seed-based smallholder out-grower business/industry in Nigeria.

The base population for selecting Nile tilapia for GIFT was composed of four wild strains in Africa (Egypt, Ghana, Kenya and Senegal) and four farmed strains in Asia (Israel, Singapore, Taiwan and Thailand) (Eknath et al. 1993; Bentsen et al. 2017). Ponzoni et al. (2011) reported more than 10% improvement in growth per generation sustained over more than six generations. GIFT has thus shown a remarkable genetic gain in growth rate and has out-performed other strains in a variety of farming systems in Asia (Bentsen et al. 2017).

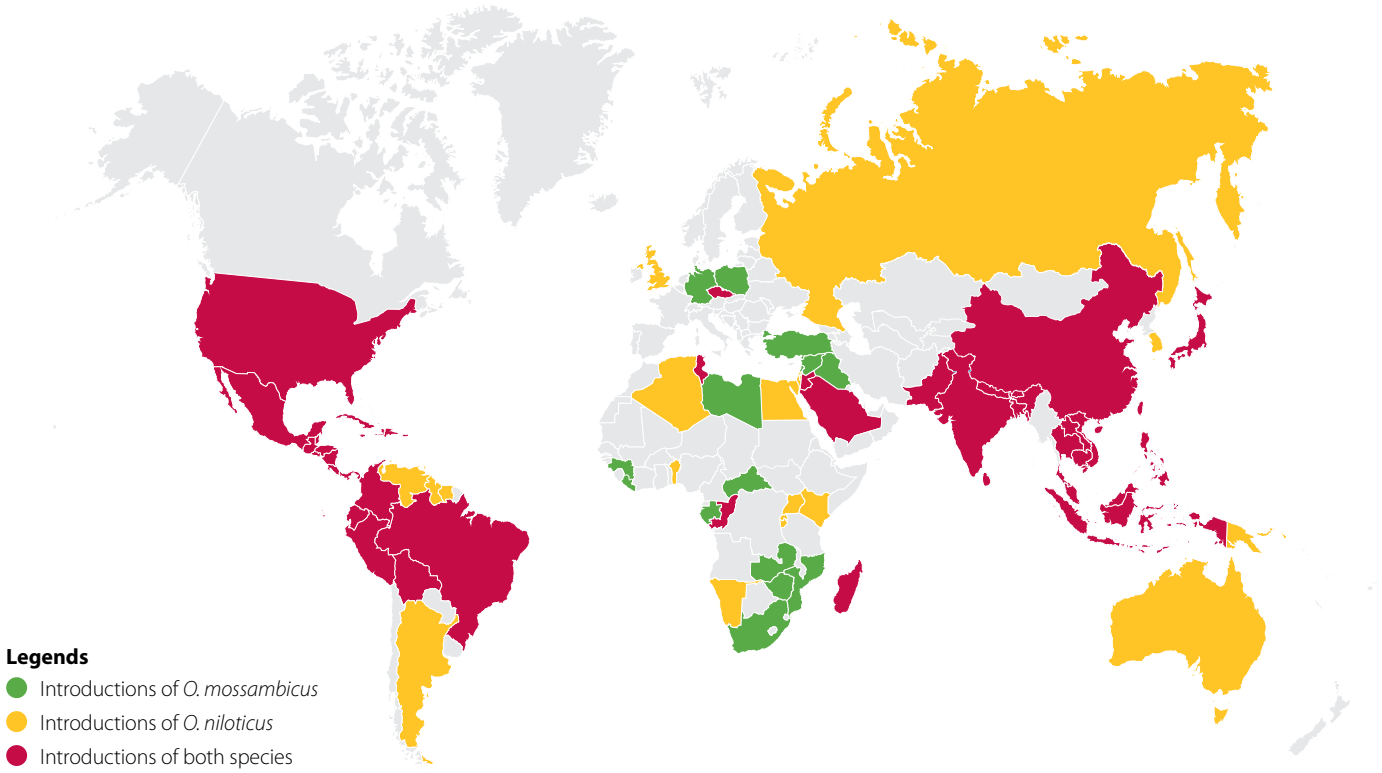
The plan is to transfer a batch of GIFT from Malaysia to Nigeria around July 2021. The fry will be produced at WorldFish's GIFT broodstock facility in Penang, Malaysia, using 17th generation GIFT as parents. Transferred fry will be kept in a designated land-based, secured quarantine facility in Nigeria's Ogun State. They will be raised with regular health checks. G2 progeny resulting from the originally transferred stock (G0) will be transferred to Delta State for breeding (non-sex reversed fry weighing 10 g) and for grow-out (sex reversed all male fry weighing 2g). G2 fish will be cultured in both land-based and water-based systems (pond and cages) in the two states. Freshwater habitats of Nigeria are suitable for the growth and propagation of Nile tilapia, and it is a native species in Nigeria and beyond.

2. Literature review

This section is a detailed review of the relevant literature dealing with the ecological and environmental impacts of previous transfers.

Originating from the Upper Nile, Nile tilapia evidently moved southward, colonizing all the Western rift lakes in Africa down to Lake Tanganyika (Philippart and Ruwet 1982). Nile tilapia exhibits several characteristics, such as feeding on and digesting phytoplankton and other microorganisms that add omega 3 fatty acids, that made a positive prognosis to label it as the "aquatic chicken" (Maclean 1984; Perschbacher 2014). According to the Database on Introductions of Aquatic Species (DIAS),[2] Nile tilapia is one of the fish species that has been deliberately introduced into various geographical regions mainly for the purpose of aquaculture development (Figure 1). It is one of the top 10 introduced species of animals in the world (Picker and Griffiths 2011).

There are about 70 species of tilapia, most of which are native to Western Africa. Of these, nine are used in aquaculture worldwide, and tilapia aquaculture production is concentrated mainly on Nile tilapia (*O. niloticus*), Mozambique tilapia (*O. mossambicus*) and blue tilapia (*O. aureus*). Of these three species, *O. niloticus* has been responsible for the significant increase in global tilapia production from freshwater aquaculture and has accounted for about 83% of total tilapia produced worldwide (Gupta and Acosta 2004). According to the Global Invasive Species Database, which is managed by the Invasive Species Specialist Group of the International Union for the Conservation of Nature's (IUCN) Species Survival Commission, Nile tilapia is a highly invasive fish that plagues a variety of ecosystems, particularly those located in the tropics, and most infestations are a result of aquaculture (IUCN 2020). Nile tilapia is often described as



Source: http://www.fao.org/fishery/dias/en.

Figure 1. The extent of introduction of *Oreochromis mossambicus* and *O. niloticus*.

a "pioneer" species, meaning that it thrives in disturbed habitats, opportunistically migrating and reproducing. These traits mean that Nile tilapia often outcompetes native species in areas where it has been introduced (CABI 2020). In DIAS,[3] there are 116 entries of introduction of Nile tilapia into various countries (Table 1). Of these, four were recorded as adverse ecological impacts, while there were four beneficial impacts and 108 unknown impacts. Sociologically, there were 25 beneficial impacts and 91 unknown impacts. Interestingly, there were no adverse sociological impacts due to introduction of Nile tilapia. When unknown impacts are also included under the beneficial category, it is evident that only about 3.4% of introductions of Nile tilapia could be treated as causing adverse ecological impacts.

Nile tilapia naturally occurs in the Nile basin (including lakes Albert, Edward and Tana), Jebel Marra, Lake Kivu, Lake Tanganyika, Awash River, various Ethiopian lakes, the Omo River system, Lake Turkana, Suguta River and Lake Baringo. In West Africa, it occurs naturally in the basins of Senegal, Gambia, Volta, Niger, Benue and Chad. This species has been widely distributed for aquaculture and sport fisheries and has established populations in many countries where introduced (Picker and Griffiths 2011).

Nile tilapia is considered an invasive species due to its aggressive spawning behavior, high levels of parental care, the ability to spawn multiple broods throughout the year and its euryphagous feeding habits (Canonico et al. 2005). Ecological effects of Nile tilapia include decreased abundance and extinction of native species resulting from habitat and trophic overlaps, competition for spawning sites (Canonico et al. 2005; Tweddle and Wise 2007), habitat destruction and water quality changes (Figueredo and Giani 2005) and hybridization with other *Oreochromis* species (Firmat et al. 2013).

Despite some instances where Nile tilapia was labeled as an introduced species, posing adverse ecological impacts, many instances of its introduction into countries have been both ecologically and sociologically beneficial. For example, in some countries, such as Brazil, Indonesia, Philippines and Sri Lanka (Sugunan 1997), Nile tilapia is reported to have contributed significantly to rural livelihoods and nutritional security.

In 1983, the First International Symposium on Tilapia in Aquaculture was held in Nazareth, Israel (Fishelson and Yaron 1983). Since then, owing to the recognition of tilapia species as candidates for aquaculture, 11 more symposiums were held until 2016, when the last was hosted in Surabaya, Indonesia.[4] These trends testify to the global importance and interest in tilapia aquaculture.

Impact of introduction	Beneficial	Adverse	Unknown
Ecological	4	4	108
Sociological	25	0	91

Source: http://www.fao.org/fishery/dias/en.

Table 1. Status of introduction of Nile tilapia as reported in DIAS.

3. ICES Code

According to the TOR, the ecological and environmental risk analysis of the proposed introduction of GIFT into Nigeria would be based on the guidelines given in the ICES Code and other relevant FAO documents.

The ICES Code provides a framework to evaluate new intentional introductions. It also recommends procedures for species that are part of current commercial practices to reduce the risk of unwanted introductions as well as adverse effects that can arise from species movement.

Accordingly, strategies for implementation of new international introductions should include the following:

1. To protect indigenous as well as previous intentionally introduced species and to meet international obligations (such as the CBD), agencies of member countries should fully implement the ICES Code and apply all regulatory measures possible to prevent unauthorized introductions.
2. To reduce illegal and unauthorized introductions, member countries are also encouraged to increase public awareness about the risks associated with importing live products.
3. To increase the reach of these management measures, countries that are not members of ICES should be encouraged to adopt them.

The ICES Code identifies three broad areas of activity:

1. recommended procedure for all species prior to reaching a decision regarding new introductions
2. if the decision is taken to proceed with the introduction
3. recommended procedure for introduced or transferred species that are part of current commercial practice.

3.1. Recommended procedure for all new introductions

This section covers the recommended procedure for all species before reaching a decision regarding new introductions.

Before introduction, a prospectus on the proposed new introduction for evaluation should be submitted, including a detailed analysis of the potential impacts on the aquatic ecosystem of the proposed introduction. This should contain, wherever possible, assessments from previous introductions, including reviews of (a) the ecological, genetic and disease impacts and relationships of the proposed introduction in its natural range and donor location, (b) the expected ecological, genetic and disease impacts and relationships of the introduction in the proposed release site and projected range, as well as vectors for further distribution, and (c) an economic assessment, where appropriate. It should also include the purpose and objectives of the introduction, the stage(s) in the life cycle proposed for introduction, the native range, the donor location, etc. WorldFish's proposal to introduce GIFT into Nigeria includes such details, and they will be continuously modified based on the inputs of the risk analyses by an independent advisory panel.

3.2. Proceeding with the introduction

This section covers the procedures that are necessary following the decision to proceed with the introduction.

According to WorldFish's proposal, the GIFT that are introduced should be used to establish a broodstock for producing progeny for further grow-out. The transferred yolk sac fry will be raised with regular health checks. Progeny from the originally transferred stock will be moved to Delta State for breeding and grow-out. Occasional assessments of genetic resources should supplement the regular health checks to ensure genetic diversity is not being lost in subsequent generations.

A monitoring program should be established in key areas where GIFT might enter Nigerian waters. Best aquaculture practices should be adopted with strong measures to prevent farmed fish from escaping. However, it is assumed that GIFT will escape or be illegally transferred to areas not authorized for its use, so monitoring the surrounding environment for GIFT will also be essential. Capacity building and awareness creation activities for key stakeholders will be necessary to reduce the risk of illegal transfer and to increase awareness of GIFT in Nigeria.

In collaboration with Nigeria's Department of Fisheries and Aquaculture, WorldFish will set up an independent national advisory team consisting of representatives from key stakeholder groups and wider civil society. As the national competent authority, the Department of Fisheries and Aquaculture will lead group meetings and dialogue toward building consensus on national implementation of the risk management plan and recommendations. This group could help establish reference points and pre-agreed actions. It could also assist in monitoring and evaluating any impacts from the introduction, similar to the ICES Working Group on Introductions and Transfers of Marine Organisms.

With the help of other experts, as necessary, the advisory team should identify water bodies in Nigeria where the use of GIFT should be restricted or prevented to avoid ecological and environmental risks. For example, there are four Ramsar sites (wetlands of international significance) in Nigeria: Lake Chad Wetlands in Nigeria,[5] the Nguru Lake (and Marma Channel) complex,[6] Oguta Lake[7] and the Upper Orashi Forests.[8]

One Ramsar site, Nguru Lake, was thought to have an endemic tilapia species, though this has not been confirmed. The Ramsar sites could be areas where farming GIFT would be restricted.

3.3. Recommended procedure for introduced or transferred species

This section covers the recommended procedure for introduced or transferred species that is part of current commercial practice.

According to WorldFish's transfer plan, 10,000 yolk sac fry of GIFT will be transferred to a secure quarantine facility in Nigeria. The plan also envisages transferring GIFT from the breeding facilities in Ogun and Delta to other areas in Nigeria. If the capacity building in these state breeding facilities is effective, it should not be necessary to transfer more GIFT from Malaysia. For transferring GIFT from the breeding facilities in Ogun and Delta to other areas of Nigeria, the receiving grow-out facilities should sign material transfer agreements indicating they will adhere to pre-agreed rules concerning further dissemination of GIFT.

GIFT fry packed for transportation (Malaysia).

4. Ecological and environmental risk analysis

The present analysis is exclusively based on the information gleaned from published research articles and reports on the status of tilapia species in Asia, Africa and other geographical regions, including their ecology, invasive status, aquaculture performance, and environmental and socioeconomic impacts. The analysis also reviewed a wealth of information on the possible implications of introducing GIFT into some countries in Asia.

Photo credit: Trong Quoc Trinh/WorldFish

Using liquid nitrogen for GIFT cryopreservation (Malaysia).

5. Results of risk analysis

5.1. Status of tilapia in Asia

Tilapia species contribute to capture fisheries in inland and lacustrine waters (predominantly reservoirs) in Asia and the Pacific. However, they have not been reported in rivers, with the exception of the artisanal fishery in the floodplains of the Sepik River in Papua New Guinea (Coates 1985). Tropical Asia has a paucity of natural lakes (Fernando and Holčik 1991), and almost all lacustrine waters in tropical Asia are reservoirs, with the exception of natural lakes in Indonesia and the Philippines. According to Fernando and Holčik (1991), tilapia are better colonized in tropical lacustrine water bodies. In this region, tilapia capture fisheries in lacustrine waters have been documented from about 20°N latitude to about 15°S longitude. The contribution of tilapia species to the total landings in individual water bodies and to the inland capture fisheries varies widely between water bodies and countries. In the Asia-Pacific, tilapia species, most notably Nile tilapia, as a group of alien species, have made a significant contribution to food production, poverty alleviation and livelihood support (De Silva et al. 2004).

On the Indian subcontinent, however, tilapia culture has developed at a slow rate after Nile tilapia was introduced into Bangladesh in 1974 (Rahman 1992) and India in the early 1980s (Jhingran 1992). In India, there is a major concern about the adverse impacts of tilapia on Indian major carps, which used to fetch much higher prices than tilapia (Jhingran 1992). Nevertheless, tilapia species are widely cultured in wastewater-fed ponds in West Bengal (Jhingran 1992; Edwards et al. 2000). Jhingran (1992) suggested that although tilapia species are considered a nuisance in India, because their widespread occurrence makes eradicating them practically impossible, the best approach would be to use them to increase inland fisheries production. In view of the immense aquaculture possibilities in India and the need for enhancing production in freshwater farming systems, India's Ministry of Agriculture formally issued guidelines for responsible farming of tilapia during December 2011 (Prabu et al. 2019). As the demand for fish is increasing, it is necessary to diversify aquaculture by including more species to increase production levels. Introducing tilapia into aquaculture systems in India is said to be advantageous, because it represents a lower level in the food chain, so its culture will be economical and eco-friendly (Ministry of Agriculture and Farmers Welfare 2015). Monosex culture of tilapia is advantageous because it grows faster and larger, and the size of males is more uniform. To this end, India's Department of Animal Husbandry, Dairying and Fisheries, in the Ministry of Agriculture and Farmers Welfare, has published a set of procedures called the Guidelines for Responsible Farming of Tilapia in India (Ministry of Agriculture and Farmers Welfare 2015).

Apart from their direct contribution to fish supplies in Asia and the Pacific, tilapia is often an affordable source of animal protein for poor, rural communities. Although only *O. mossambicus* and *O. niloticus* have contributed significantly to inland capture fisheries in Asia, tilapia species do not dominate fisheries throughout all the reservoirs and lakes on the continent. For example, they do not dominate the fisheries in any of the lacustrine water bodies in Thailand, in contrast to those in Indonesia, the Philippines and Sri Lanka (De Silva et al. 2004). The prevailing opinion is that riverine species are poor colonizers and that lacustrine or lacustrine-adapted fish species, such as tilapia, are successful colonizers in lacustrine habitats in reservoirs, producing high fish yields (Fernando and Holčik 1991). However, this notion needs to be re-visited because of the poor contribution of tilapia to fish production in Thai and Indian reservoirs with rich ichthyofaunal diversity. Ferreira et al. (2015) analyzed the production, environmental effects and economic optimization of Nile tilapia (*O. niloticus*) and white shrimp (*Litopenaeus vannamei*) pond culture in Thailand and concluded that sustainable expansion of aquaculture would be possible for both species.

In Asia, as elsewhere, where tilapia species have been introduced, there is a high probability that hybridization occurs among co-habiting tilapia species in natural or quasi-natural waters. This has been demonstrated in tilapia populations in reservoirs in Sri Lanka (De Silva and Ranasinghe 1989) and in the Philippines (Macaranas et al. 1986). Amarasinghe and De Silva (1996) observed

that the fecundity of hybrids was significantly lower than that of the parent species, in the case of *O. mossambicus* and *O. niloticus*. Based on these findings, the authors hypothesized that this could reduce the reproductive capacity of the populations over the long-term. Consequently, this would perhaps be detrimental to the maintenance of the relatively successful fishery for tilapia species in Sri Lanka's reservoirs.

In Kaptai Lake, a large reservoir in Bangladesh, the decline of the indigenous carp fishery is attributed to an increase in Nile tilapia landings (De Silva et al. 2004). However, these accounted for less than 1% of the total fish yield in the reservoir. Furthermore, a thorough study has not been undertaken in this case, including aspects on increased use of destructive gear and landing of indigenous carps during their spawning migration. Significant interspecies dietary overlap was found between Nile tilapia and small indigenous fish species, such as *Amblypharyngodon mola*, *Chela cachius* and *Puntius sophore*, in earthen ponds in Bangladesh. As such, there is potential for Nile tilapia to compete with indigenous fish species when space and other resources are limited (Ahmad et al. 2010). Although tilapia introductions have brought about certain faunal changes in certain isolated instances, the introduced tilapia were not the primary cause of the changes. Generally, deliberate and accidental tilapia introductions into the Asia-Pacific have been positive, because they have created profitable fisheries in most countries in the region. In these cases, they generated employment opportunities and provided an affordable and easily accessible animal protein resource to the poorer sectors of the community. In Pakistan, several introduced alien exotic fish species, including three species of tilapia (*O. aureus, O. mossambicus, O. niloticus*) in warm waters, are becoming invasive in the freshwater biomes of the Punjab and other provinces because of their potent reproductive potential and feeding competition with the native freshwater fish fauna (Khan et al. 2011). Due to these introductions, native fish species of economic value are under threat (Khan et al. 2011), namely *Channa marulius, Wallago attu, Rita rita, Sperata seenghala (=sarwari), Gibelion catla, Cirrhinus mrigala* and *Labeo rohita*.

China is the largest tilapia producer in the world. The majority of production is located along the southeastern coast, including the provinces of Guangdong, Guangxi, Hainan and Fujian. In 2010, these four provinces produced 1.198 million metric tons, representing 90% of national production. Although an exotic species in China, tilapia is the sixth-largest production subsector after silver carp (*Hypophthalmichthys molitrix*), bighead carp (*H. nobilis*), grass carp (*Ctenopharyngodon idella*), common carp (*Cyprinus carpio*) and crucian carp (*Carassius auratus*). Nile tilapia (*O. niloticus*) is the most popular species used for aquaculture in the country (Liu et al. 2013). In China, it is one of the major species cultured in freshwaters that exceeded annual production of 25,000 t^{-1}. *O. niloticus* is reported to be cultured mainly in China's Fujian, Guangdong, Guangxi, Hainan and Yunnan provinces (Wang et al. 2015).

In Bangladesh, a new avenue for extensive tilapia farming became possible with the introduction of the GIFT strain in 1994 through WorldFish (then ICLARM) under the Dissemination and Evaluation of Genetically Improved Tilapia Species in Asia (DEGITA) project (Hussain 1996). Hussain (2009) reported that tilapia production increased from 2140 t in 1999 to 66,767 t in 2007 and was confident that Bangladesh would become one of the leading countries in Asia in tilapia production in the near future. Recently, WorldFish has been implementing a broodstock development program in Sri Lanka in collaboration with the National Aquaculture Development Authority (NAQDA) of the Ministry of Fisheries and Aquatic Resources. One component of this project consists of introducing and further improving the performance of GIFT in Sri Lanka. The breeding program involved transferring 50 GIFT families, with 20 to 30 fish per family, from the latest generation of selection in Malaysia to NAQDA's Dambulla Breeding Centre. A cohort breeding design, in combination with rotational mating of males, has been practiced since 2007. So far, the GIFT fish have undergone four generations of selection for increased harvest weight in Sri Lanka (Nguyen et al. 2011). The GIFT project has increased inland fisheries and aquaculture in the country. In 2000, only 10% of Sri Lanka's fish production came from inland fisheries and aquaculture. By 2010, that proportion had increased to 13.5%. During the same period, the increase in freshwater fish production went from 36,700 to 51,390 t.

Indonesia is the second-largest producer of Nile tilapia in the world after China (FAO 2017). Due to intensive aquaculture, Nile tilapia now

occurs in all brackish waters and freshwaters of mainland Indonesia. It was first introduced into the Philippines in 1972 and rapidly gained popularity with farmers and consumers. It is now the main species of tilapia farmed in the country. The Philippines is the third-largest producer in Asia and the fourth-largest in the world. Based on production data from 1985 to 2001, the supply of tilapia in the Philippines is all produced domestically—about 79% from aquaculture and the remainder from inland fisheries. Total tilapia production in this period grew on average by 6% annually. In 2001, freshwater fishponds and cages accounted for 91.2% of the 106,618 t of total tilapia aquaculture production. In 2013, the Philippines produced 316,536 t of tilapia with a value of USD 669.8 million. Tilapia production from freshwater ponds increased from approximately 14,000 t in 1985 to 66,000 t in 2002. In 2013, tilapia culture surpassed 270,000 t in the Philippines, where tilapia are found in rivers, ponds and lakes. Pond farming of tilapia began in the Central Luzon ponds in the 1950s. Advances in culture techniques led to rapid production increases, and a low-cost sustainable GIFT strain helped spur production.[9]

The principal nations in Asia and the Pacific that have adopted tilapia culture are China, Indonesia, the Philippines, Thailand and Taiwan. Tilapia is produced under diverse production environments in Bangladesh, China, the Philippines, Thailand and Vietnam. Changes in Nile tilapia production in these countries indicate that China currently accounts for over 70% of the region's production, an increase from 39% in 1988 before the reported rapid increase in the country's Nile tilapia culture. This has led to a decreased share of production from the other countries in the region, even when production has exhibited growth. In the Philippines, for example, the proportional contribution to regional Nile tilapia production was 27% in 1988 but only 10% in 2002, even though production increased from 27,000 t to 104,000 t over the period.

Tilapia farming is dominated by small- and medium-scale farmers employing semi-intensive systems. Semi-intensive systems of tilapia culture are appropriate for the socioeconomic conditions prevailing in these countries (Dey et al. 2000a). The majority of fish farmers in Bangladesh, China, Thailand and Vietnam raise tilapia in ponds using polyculture systems, while the tilapia farmers in the Philippines culture fish in ponds and cages using monoculture systems. Nile tilapia is commonly cultured in backyard and/or home garden ponds to supplement the income of poor households as well as provide a fresh source of animal protein to the family. In such situations, the cultured stock is often fed with kitchen waste and supplemented by relatively readily available, often low-cost agricultural by-products, such as rice bran. Tilapia farming is a very profitable activity both in monoculture and polyculture systems. In the integration of commercial poultry farming with Nile tilapia culture, cultured stocks are not fed but depend on poultry waste and the natural food production in eutrophic ponds.

Nile tilapia is also being increasingly used in rice-fish culture and has been reported to enhance the overall yields in practices in China (Banghuai and Qianlong 1995) and Bangladesh (Gupta et al. 2002). The productivity, cost of production and profitability of tilapia farming vary considerably across countries, production environments and culture systems. The productivity and profitability of tilapia farming are higher in China and Thailand compared to the other countries (Dey et al. 2000b). The two most significant costs in tilapia monoculture (both in ponds and cages) are feed and then fry/fingerlings, while the cost of fry/fingerlings is the most significant cost in pond polyculture in most of the countries. Consumers in these countries show a strong preference for tilapia, except in Bangladesh. Tilapia is consumed mainly by relatively poor people because of its low price compared to other fish species, indicating high potential for tilapia farming in Asian countries (Toledo et al. 2008). The success of Nile tilapia as a cultured species group throughout many tropical countries can be primarily attributed to the following (De Silva et al. 2004):

- Culture under extensive, semi- and/or intensive practices is relatively easy, so it is relatively less limited by the economic status of the farmer compared to most other finfish species.
- Relevant species exhibit many of the desirable traits expected of a species suitable for culture, such as a relatively high growth rate, wide range of tolerance to physicochemical characteristics, resistance to disease and ease of propagation.
- Tilapia has a moderately high dress-weight ratio.
- It also has a long shelf-life.

- As a white fish, tilapia is mild and lends itself to industrial preparations better than most other white fish (Picchietti 1996).

In addition to these points, most of the commonly cultured tilapia species are easily weaned onto artificial feeds. The group has the ability to derive its nutrition effectively from the natural food in rearing systems, particularly in ponds. This attribute makes it the foremost choice in home-garden and/or backyard small-scale, subsistence fish culture in developing countries such as Bangladesh, Vietnam. In the freshwater wetlands of the Mekong region in Southeast Asia, native fish biomass was not affected by stocking non-native species, including Nile tilapia, and no significant impacts on native fish species richness, diversity indices, species composition or feeding guild composition were detected (Arthur et al. 2010). On the other hand, Canonico et al. (2005) have indicated that despite potential or observed benefits to human society, tilapia aquaculture and open-water introductions cannot continue unchecked without further exacerbating damage to native fish species and biodiversity.

5.2. Status of tilapia in Africa

Nile tilapia is native to tropical and subtropical Africa as well as the Middle East. It is widely distributed in the Nile and Niger river basins and in lakes Tanganyika, Albert, Edward and George, as well as in many smaller drainages and lakes in western and eastern Africa. It is also found in the Yarkon River in Israel (Trewavas 1983). Nile tilapia is one of the world's most important food fish. Owing to its hardy nature and wide range of trophic and ecological adaptations, it has been widely introduced for aquaculture, augmenting capture fisheries and sport fishing, and is now found in every country in the tropics. Nile tilapia is often described as a "pioneer" species, meaning that it thrives in disturbed habitats, opportunistically migrating and reproducing. As such, it often outcompetes native species in areas where it has been introduced. On the African continent, Nile tilapia is reported to occur in 40 countries (Pullin et al. 1997). Of these, Nile tilapia is native to 19 African countries, whereas the rest of the countries possess introduced populations.[10]

In Lake Victoria, two native cichlid species (*Oreochromis variabilis, O. esculentus*) are no longer present except in a few satellite lakes. To compensate for the decreasing catches of native tilapiines (*O. variabilis, O. esculentus*) in the 1950s, exotic tilapiines (*O. niloticus, O. leucostictus, Coptodon zillii, C. rendalii*) were introduced into Lake Victoria, where they were expected to fill empty niches (Welcomme 1967). Following the fish introductions of the 1950s and early 1960s, *O. niloticus* has become the most abundant and commercially important species among the tilapiines, and the only one that has managed to co-exist with the Nile perch in lakes Victoria and Kyoga (Balirwa 1998). The indigenous tilapiines declined as a result of competition for food, spawning sites and nurseries, and hybridization with the alien species (Welcomme 1967; Ogutu-Ohwayo 1990). Most of these populations are considered either endangered or have suffered genetic modification by hybridization with closely related introduced species. Tilapia species are well known for their hybridizing abilities in the natural environment when native species are in contact with introduced species. The hybrids between *O. niloticus* and *O. variabilis* were observed before the latter species had disappeared from the lake. It also seems likely that *O. esculentus* hybridized with *O. niloticus* (Wasonga et al. 2017). Nile tilapia now dominates, whereas most of the other tilapiines are rarely caught in the lake (Njiru et al. 2005). In Lake Victoria, several factors could be contributing to an increase in Nile tilapia biomass: (a) increasing recruitment capacity from more feeding and breeding areas of Nile tilapia, (b) availability of suitable food and the species occupying vacant niches left by declining stocks of indigenous species, especially the haplochromines, and (c) the diversification of diets of the previously herbivorous tilapia to include insects and fish (Njiru et al. 2008). On the other hand, tilapia lake virus (TiLV) has emerged as a significant viral disease of farmed Nile tilapia having the potential to impede expansion of aquaculture production. The first detection of TiLV infection by polymerase chain reaction (PCR) in farmed and wild Nile tilapia from Lake Victoria was reported by Mugimba et al. (2018).

In Tanzania, experimental evidence has found that non-native Nile tilapia would threaten native tilapia species through dominance in interference competition (Champneys et al. 2020). In Kenya, Nile tilapia is labeled as a fully invasive species, with individuals dispersing, surviving and reproducing at multiple sites across a wide spectrum of habitats and extent of occurrence (Okwiri et al. 2019).

In Lake Nasser, Israel, the multi-species fishery is dominated by *O. niloticus* and *Sarotherodon galilaeus*. *O. niloticus* and *S. galilaeus* landings increased from 278 t in 1966 to a maximum of 30,529 t in 1981. Subsequently, the tilapiine catch decreased to about 13,000 t in 1989. This decrease was thought to be mainly due to the decline in the water level during the drought from 1984 to 1988, which shortened the shoreline, increased its slope and thereby shrank the fishing grounds. However, tilapiine landings increased again to 29,389 t in 1991, but then fell to only 8281 t in 2000. As the tilapiines *O. niloticus* and *S. galilaeus* (contributing about 85% of the catch) inhabit shallow inshore areas, their population was profoundly affected by reservoir levels (van Zwieten et al. 2011).

In Lake Volta, Ghana, the reservoir is estimated to provide 90% of national freshwater fish production. The most numerous and commercially important fish species are *O. niloticus, S. galilaeus* and *Synodontis* (=*Hemisynodontis*) *membranaceus* (van Zwieten et al. 2011). Catch estimates of Lake Volta's fishery currently range from 40,000 to 271,000 t, but production figures are at least much higher than 100,000 t. The total annual production of the reservoir could fluctuate greatly as a result of high annual variability in the area flooded by the annual increases in discharge (van Zwieten et al. 2011).

Nile tilapia is already established in the lower catchment of the Limpopo River basin of South Africa, where indigenous congenerics are at risk of extinction through hybridization and competitive exclusion. Nile tilapia, therefore, poses an ecologically unacceptable risk to river systems in the upper catchment where it has yet to be established (Zengeya et al. 2013).

5.3. Status of tilapia species in other geographical regions

Tilapia aquaculture in the Americas began with small-scale culture for subsistence farming in the late 1960s and 1970s, and large-scale production and international trade of tilapia products developed in the 1980s and 1990s. *O. mossambicus*, which was the first species widely distributed in the Americas, still accounts for a significant proportion of tilapia production. In the future, there will be increases in the number of strains or breeds of *O. niloticus* and red hybrid strains available. The volume of tilapia produced in the Americas is likely to double in the next 10 years, most of which will occur in tropical regions. In both the tropics and temperate zones, production will become more intensive, with more complete diets, aeration, water reuse and disease control as important factors (Fitzsimmons 2000).

Tilapia aquaculture in the Americas will continue to grow rapidly. Mexico and Brazil will be the major producers and consumers, while the US will be the third-largest producer, third-largest consumer and the largest importer (Fitzsimmons 2000). Based on a study carried out in a tropical reservoir in Brazil, Vasconcelos et al. (2018) have shown that Nile tilapia could suppress phytoplankton and zooplankton biomass in tropical lakes and reservoirs, though the magnitude of this effect would depend on plankton biomass and size-structure. In neotropical reservoirs, the use of non-native fish, including Nile tilapia, in fish farming activities was the primary driver of fish introductions (Ortega et al. 2015). Esselman et al. (2013) investigated spatiotemporal patterns of tilapia spread into 29 drainage basins in Belize as well as parts of Guatemala and Mexico. Drawing on field data and interviews with fishers, they confirmed the presence of tilapia (predominantly *O. niloticus*) at 78 sites in nine of the drainage basins. They reported that human movement of fish for aquaculture was identified as a primary cause of dispersal, which interacted with flooding as an important secondary cause. Esselman et al. (2013) recommended that more stringent regulations of aquaculture activities, pro-active fisheries management and development of policies should be in place to screen potentially invasive species before importing them to avoid additional releases of tilapia and further spread in the region. As the neotropical region has a rich native ichthyofauna (estimated at more than 7000 species), Pelicice et al. (2014) suggested that suitable native species should be used instead of using non-native species for aquaculture development. However, Ortega et al. (2015) have indicated that, in the short term, it is unlikely that fish farming will switch to native species farming. Instead, they suggested that fish farming should follow more effective preventive measures throughout all processes from enterprise establishment to processing fish for consumption. Ortega et al. (2015) further stated that it is of utmost importance to take measures to avoid the release or accidental escape of the cultivated individuals at all fish farming stages and that neotropical

fish farming has to become more professional, as the lack of professionalization leads to mistakes that culminate in non-native introductions.

Deines et al. (2016), who reviewed ecosystem services associated with global tilapia introduction, have shown that tilapia introductions often represent a trade-off between positive and negative ecosystem services. According to this review, the ecological effects may be similar over much of the introduced range of tilapia. But socioeconomic benefits are not uniform, and often there are ambivalent perspectives about the net socioeconomic value of tilapia introductions, which requires careful consideration of local context in decisions about tilapia introductions. In Nicaragua, the escape of Nile tilapia from aquaculture and its subsequent establishment cut native cichlid catches more than 50% (McKaye et al. 1995). Progressive introductions of different species, including Nile tilapia, drastically decreased native fish in Madagascar's Lake Alaotra (Lévêque 1997) and resulted in changes in phytoplankton communities in Brazil (Figuerdo and Giani 2005).

One of the serious impacts of Nile tilapia introductions in Africa is known to be via hybridization with other *Oreochromis* species. Hybridization between *O. niloticus* and the endemic *O. variabilis* (Welcomme 1967) and *O. esculentus* (Mwanja et al. 2001) has been reported in the Lake Victoria basin. In the Limpopo River system of South Africa, extensive hybridization of introduced Nile tilapia with native *O. mossambicus* has been reported (Firmat et al. 2013). Nile tilapia introductions have also resulted in hybridization with *O. andersonii* and *O. macrochir* in the Kafue River in Zambia (Deines et al. 2014). Tweddle (2010) reported that *O. niloticus* has almost replaced the native *O. mortimeri* in Zimbabwe's Lake Kariba. Extensive hybridization with Nile tilapia is recognized as a primary threat to *O. mossambicus*, which the IUCN has red-listed as "near threatened" (Firmat et al. 2013).

The present analysis is exclusively based on the information gleaned from published research articles and reports on the status of tilapia species in Asia, Africa and other geographical regions.

Collecting milt from male GIFT (Malaysia).

6. GIFT strain

GIFT was the result of a carefully conducted genetic selection and improvement program based on broodfish collected from four African countries (Egypt, Ghana, Kenya and Senegal) and four commercial *O. niloticus* strains (from Israel, Singapore, Taiwan and Thailand) used in the Philippines (Eknath et al. 1993; Dey and Gupta 2000). Through a combined family and within-family selection strategy, the GIFT strain emerged and is purported to have an 85% cumulative genetic gain compared to the base population (Eknath et al. 1993). The development of a better strain by itself does not complete the task, particularly in regions where tilapia culture is widespread, which are often rural and very diverse, unless the findings are extended to practitioners to enable them to reap the benefits. This was achieved through DEGITA, coordinated by WorldFish and involving five Asian countries. The project aims to ascertain the following:

- genetic, socioeconomic and environmental aspects of the production of GIFT in different agro-ecological conditions and culture systems
- the overall impact of GIFT on different socioeconomic groups, such as farmers and consumers
- dissemination of the strain among small farmers if found to be superior to locally available strains.

The GIFT strain performed better in all countries. For example, on an average farm, the harvesting weight of GIFT was 18% higher in China and 58% higher in Bangladesh. It was suggested that the better performance of the strain, after accounting for the wide heterogeneity of production environments, input levels and other factors, was solely the result of its superiority.

6.1. Possible implications of genetically improved strains

Unfortunately, there is no information available on the impact of tilapia culture in general, but GIFT has been introduced into several other Asian countries. Nile tilapia is widely distributed in Asia already, and there are no robust analyses to indicate that it has been responsible for the decline of indigenous species. As such, GIFT might not cause any negative impacts on the environment when introduced and/or established. In contrast, it is possible that GIFT, because of its genetic superiority, could be more invasive and would increase its range of distribution, bringing about detrimental environmental impacts that were not evident with Nile tilapia. The reverse also could occur because of its rather specialized traits, such as its fast growth, which may have reduced fitness in the wild (De Silva et al. 2004). Wijenayake et al. (2008) reported that GIFT did not perform well in culture-based fisheries in non-perennial reservoirs of Sri Lanka, where stocked fish were not given supplementary feed. In Bangladesh, higher survival and production of GIFT were influenced by their better use efficiency of natural food, especially benthos and periphyton (Haque et al. 2016).

Tilapia culture in Africa is based mostly upon native Nile tilapia populations. Having faster growth, GIFT can yield significant increases in tilapia production in Africa. As a result, it is believed that substantial improvements in aquaculture production in Africa can be achieved through aquaculture of the strain. Yet while development economists see the potential for food security and poverty reduction from culturing GIFT, conservationists are wary of potential ecological and genetic impacts on receiving ecosystems and native stocks of tilapia. Based on a comprehensive economic analysis, Anash et al. (2014) have shown that improvements in management practices and infrastructure could increase the yield and profitability of the local strains even if genetically improved strains are not introduced.

When a non-native species is introduced into a community, its invasive success is mainly determined by the species diversity of the recipient community through biotic resistance (Elton 1958). Together with abiotic environmental factors, biotic resistance can often explain the failure of non-native species to invade a novel ecosystem (Catford et al. 2009). Resistance of a native community to invasion from a non-native species is related to competition, predation

and parasitism (Elton 1958; Simberloff 2011). Furthermore, how the effects caused by invasive species on native communities and ecosystems are interpreted depends on human values. There is currently a debate about whether invasive species should be treated in the same way as native ones (Valéry et al. 2013). In contrast, invasive species are known to create impacts only after time lags (Simberloff et al., 2013) and impacts caused by invasive species would be more severe and more frequent than those caused by excessive growth of native ones (Simberloff et al. 2012; Hassan and Ricciardi 2014). Simberloff and Vitule (2014) argue that invasive species are fundamentally different from most native ones. Due to these controversial opinions, the actual status of invasiveness of non-native species should be viewed through evidence-based evaluation.

Rearing tilapia fry in hapas in concrete tanks (Nigeria).

7. The ecological and environmental risk management plan

7.1. Balancing ecological risks and economic gains

Despite the well-known adverse impacts of species introductions, such as their effects on biodiversity, and possible introduction also of new pathogens and diseases, production of Nile tilapia continues to contribute significantly in many countries, possibly due to its relative ease to domesticate and culture (Cuvin-Aralar 2016). Nearly all worldwide introductions of Nile tilapia are for aquaculture (Canonico et al. 2005). Measures to address possible adverse impacts of species introductions in inland waters should be undertaken by conducting a science-based risk assessment before introduction and also balancing ecological risk and economic gains through a valuation of ecosystem goods and services of inland water bodies (Cuvin-Aralar 2016).

As mentioned by Welcomme and Vidtayanom (2003), there are many reasons for introducing exotic species into freshwaters, including providing new species that have high productivity or higher market value than the local species. Introducing the GIFT strain into Nigeria is essentially meant to increase the productivity of inland aquaculture.

Dey (2000) assessed the possible impacts of introducing and culturing GIFT in five Asian countries: Bangladesh, China, the Philippines, Thailand and Vietnam. The findings of the analysis were that adopting the GIFT strain would increase both tilapia production and total fish production, enhance the profitability of fish farming, lower the price of tilapia, and increase consumption of tilapia and other fish for consumers and GIFT farmers. It would also improve the economies of the five countries. In a similar vein, as a whole it can be considered that introducing GIFT into Nigeria might result in similar positive impacts in terms of tilapia production and consumption, as well as improving the national economy.

7.2. Potential to alleviate food insecurity, malnutrition and poverty

Aquaculture, especially of tilapia, has the potential to play a leading role in the fight against food insecurity, malnutrition and poverty in Africa. In 2014, Africa produced about 1.74 million metric tons of fish from aquaculture, which was less than 2% of global production. The major producer was Egypt (about 1.1 million metric tons). The other major aquaculture producers were Nigeria (313,000 t) and Uganda (111,000 t). Almost half (43.6%) of African aquaculture production is of Nile tilapia. Much of the tilapia and catfish are semi-intensively produced, which requires additional feeding. There is considerable motivation to develop aquaculture in sub-Saharan Africa, including small-scale cage farming in large lakes as well as small-scale fish farming integrated into family agriculture systems (AFD/EC/GIZ 2017).

7.3. Sharing benefits of GIFT R&D with African countries

Adopting the GIFT strain would benefit both producers and consumers in each country where it is introduced. However, Africa benefits the least from the GIFT strain, even though many African countries have high potential for tilapia farming. WorldFish's policy used to be not to introduce GIFT into countries where Nile tilapia is indigenous, out of concern that interbreeding with locally adapted native populations might compromise wild aquatic genetic diversity (Gupta and Acosta 2004). The ADB conducted an impact evaluation study on the development of genetically improved farmed tilapia and their dissemination in selected countries (ADB 2005). According to this study, the legitimacy and ethics of discouraging the introduction of GIFT into African waters, where they would likely interbreed and compromise the genetic integrity of important wild tilapia genetic resources, is questionable, mainly due to the fact of issues related to benefit sharing. Africa supplied Nile tilapia genes for the development of GIFT, which is a legitimate reason for sharing the benefits of GIFT R&D with African countries. Such benefit sharing can be addressed by disseminating and providing support for applying GIFT methods to new tilapia breeding programs in Africa that are based on African strains, not by shipping GIFT directly from Asia to Africa (Pullin et al. 2001; ADB 2005). If GIFT is not introduced into African countries, the people of these countries will be deprived of the benefits from using the improved strain. Moreover, in view of the growing

interest in aquaculture in many African countries, there is a great disadvantage of not introducing the GIFT strain. Otherwise, they might introduce other fish that could cause more damage to biodiversity and the environment. As such, there is no point in keeping the GIFT strain away from Africa if the genetic improvement of tilapia or introduction of any other genetically improved fish species is going to occur on the continent (Acosta and Gupta 2010).

In WorldFish's program of GIFT introduction, there is a follow-up activity to ensure the long-term effectiveness of the breeding program and to develop national strategies for effective dissemination and maintenance of the improved strains (Acosta and Gupta 2010). As there was pressure to disseminate the actual GIFT germplasm to Africa in 2007, WorldFish changed its policy and approved the transfer of GIFT from Asia to Africa, making the strain available to any African government that could demonstrate procedures to manage environmental and biodiversity risks, among other conditions (WorldFish 2007). In fact, WorldFish has ongoing programs, supported by the UNDP, for transferring GIFT-related technologies from Asia to Africa (currently including Côte d'Ivoire, Egypt, Ghana and Malawi) for their use with native African tilapia (ADB 2005).

7.4. Compliance with the Convention on Biological Diversity

The receiving country, however, must display compliance with the CBD, while indicating the development objective it intends to achieve with the GIFT introduction. The CBD requires parties to prevent the introduction of alien species that threaten the ecosystems, habitats or species, or to control or eradicate them (Hill and Sendashonga 2004). However, there are cases where full compliance with the CBD has not been put in place when the GIFT strain has been used for aquaculture development. For example, Amaraweera et al. (2021) reported pond culture of GIFT in the flood prone Nilwala river basin in southern Sri Lanka without any precautionary approaches to prevent GIFT from escaping into natural habitats during floods. Because of this risk, when introducing GIFT into an African country, the recipient nation should strictly comply with the objectives of the CBD while addressing the development objectives. In Nigeria, aquaculture development has been driven by social and economic objectives, such as improving nutrition in rural areas, generating supplementary income, diversifying income activities and creating employment (Anthony and Richard 2016). Nigeria is among the largest fish consumers in the world, with over 1.5 million metric tons of fish consumed annually, of which about 60% is imported, while domestic annual fish catch is estimated at 450,000 t. Due to this huge gap in fish production, there is a significant motivation for the government and the private sector to implement measures to increase domestic production (Kaleem and Sabi 2020). As such, introducing GIFT to increase aquaculture production in Nigeria could be an important strategy. Being a domesticated strain developed for aquaculture development, GIFT possesses characteristics that are beneficial to aquaculture, such as surface feeding on pelletized food and an inability to compete with wild stocks for acquiring natural food. However, these characteristics may not be beneficial in the wild. Wijenayake et al. (2008) have found that in terms of specific growth rate and survival rate, GIFT did not perform well in culture-based fisheries development initiatives in non-perennial reservoirs of Sri Lanka using a combination of fish species, including Indian major carps and GIFT. This might be because the characteristics of GIFT favor aquaculture, which may reduce their fitness in the wild. As such, the chance of adverse impacts of newly introduced GIFT on native stocks would be remote.

7.5. Changing anti-tilapia attitudes

To sustain tilapia aquaculture in Nigeria, anti-tilapia attitudes must be changed. Nigeria is the second-largest producer of farm-raised tilapia in Africa after Egypt (El-Sayed 2006; Fagbenro et al. 2010; Kaleem and Sabi 2020). There are over 25 species of tilapia in Nigeria, out of which about six are used for aquaculture, namely *Coptodon zillii, C. guineensis, Sarotherodon galilaeus, S. melanotheron, Oreochromis niloticus* and *O. aureus*. The aquaculture industry in Nigeria is very promising, as there are water bodies, some institutional commitment and a high demand for fish, among others. Despite some gains made by the country and the huge potential of the aquaculture sector, it has not been fully realized due to constraints such as low technology adoption, inadequate supply of fingerlings and high cost of fish feed (Kaleem and Sabi 2020). To sustain tilapia aquaculture in Nigeria, it is necessary that

anti-tilapia attitudes, which are illogical, are changed and that environmentally compatible enterprises, well integrated with other development initiatives, are introduced. In many of the countries in the Asia-Pacific that received GIFT, there are introduced populations of Nile tilapia. Since GIFT was introduced in these countries, developing and disseminating the strain have proven to be a successful investment with economic returns (Acosta and Gupta 2010). According to Acosta and Gupta (2010), in many developing countries where GIFT is already available, the strain is responsible for increasing tilapia production from a wide range of farming systems and fish supply to a wide range of consumers, including the poor. In many of these countries, such as Thailand, Philippines, Vietnam (Rutten et al. 2004; ADB 2005) and China (Li 2002), GIFT generally performed better than the existing farmed tilapia. As such, introducing GIFT into Nigeria will undoubtedly be a valuable addition to increase inland fish production.

7.6. Better practices for tilapia farming and husbandry

Generally, farming tilapia does not pose adverse environmental impacts. However, as in all forms of fish farming, poor fish husbandry practices can contribute to water pollution and eutrophication. Good practices are therefore essential for minimizing adverse environmental effects from tilapia farming. According to Ansah et al. (2014), in terms of development economics, there is great potential for food security and poverty reduction in Africa through culturing GIFT. However, from a conservation point of view, potential ecological and genetic impacts are predicted on receiving ecosystems and native stocks of tilapia. Ansah et al. (2014) have stated that improvements in management practices and infrastructure could increase the yield and profitability of the local strains even if genetically improved strains are not introduced.

7.7. Biosafety

In terms of the biosafety of international transfers of alien species, including genetically improved farmed fish such as GIFT, the potential environmental risks including the following:

- spread of diseases and parasites
- adverse impacts on natural environments and their biodiversity through diseases and parasites, and through predation, competition for food and spawning grounds
- hybridization
- habitat modification.

According to the ADB (2005), the development and dissemination of GIFT, GIFT-derived and other Nile tilapia do not appear to have caused any significant adverse impacts on existing aquaculture or on the natural environment and biodiversity in the Asia-Pacific. The region is rich with freshwater biodiversity and habitats, having sufficient wild genetic resources (in the form of original gene banks) for future breeding programs of Asian farmed fish. Because of this, appropriate policies, rules and regulations and implementation mechanisms should be in place for aquaculture development with long-term biosafety, quarantine and other environmental safeguards.

One indirect environmental effect of GIFT in aquatic habitats, though anecdotal, is turbidity in clear waters and a lower amount of available light in the water, which affects all organisms relying on photosynthesis. Another effect is the discharge of high nutrient excreta, which causes severe water pollution, specifically high biochemical oxygen demand, elevated nitrogen, phosphate, and suspended solids.

As these biosafety issues are also relevant to Africa, introducing GIFT into Nigeria should be coupled with formulating and implementing appropriate policies, rules and regulations for environmental safeguards.

The ADB (2005) conducted an impact evaluation study on the development of GIFT and its dissemination in selected countries. Based on the experience with GIFT and GIFT-derived strains, the study stated that the following seven enabling conditions must be in place in a receiving country to develop and disseminate GIFT in a sustainable way:

1. the existence of a strong national institute, with adequate capabilities in fish genetics research
2. adequate resources and continued commitments for implementing national fish breeding programs

3. multilevel networks and broad-based partnerships (including those between private and public institutions) for production and distribution of genetically improved broodstock and seed
4. market-driven demand for the farmed species concerned and prospects for gaining attractive returns from fish farming
5. supportive policies, facilities and infrastructure for fish farming
6. access by fish farmers to livelihood assets (human, social, natural, physical and financial capital) and to support services
7. enforcement of biosafety and environmental safeguards.

It is recommended that the policies are formulated, and investments are promoted to ensure these enabling conditions are fulfilled for sustained genetic improvement in aquaculture and to achieve sustained benefits for producers, intermediaries and consumers.

Photo credit: Trong Quoc Trinh/WorldFish

GIFT broodstock in hapas (Myanmar).

8. Summary of the ecological/environmental risk assessment

The results of the ecological and environmental risk assessment are summarized under different risk assessment considerations in Table 2.

Risk assessment framework consideration	Synopsis	References
Invasive success of the non-native GIFT in the recipient country	Introduced Nile tilapia has become the most abundant and commercially important species among the tilapiines, and it is the only species that has managed to co-exist with the Nile perch in lakes Victoria and Kyoga. In Bangladesh and Pakistan, Nile tilapia competes with indigenous fish species when space and other resources are limited. In many countries, introduced Nile tilapia is considered as an invasive species. Nevertheless, tilapia introductions often represent a trade-off between positive and negative ecosystem services.	Balirwa (1998) Ahmad et al. (2010); Khan et al. (2011) McKaye et al. (1995); Lévêque (1997); Deines et al. (2016)
	Nile tilapia is widely distributed in Asia already, and there are no robust analyses to indicate that it has been responsible for the decline in indigenous species.	De Silva et al. (2004)
	After the introduction of GIFT fish in many countries in the Asia-Pacific, developing and disseminating the strain have proven to be a successful investment with economic returns. Adoption of the GIFT strain in some Asian countries has increased both tilapia production and total fish production, enhanced the profitability of fish farming, lowered tilapia prices, increased consumption of tilapia and other fish for consumers and GIFT farmers, and improved the economies.	ADB (2005); Rutten et al. (2004); Acosta and Gupta (2010)
	Characteristics such as surface feeding on pelletized food and an inability to compete with wild stocks for acquiring natural food may not be beneficial for GIFT to perform in the wild. In culture-based fisheries development initiatives in non-perennial reservoirs in Sri Lanka, GIFT did not perform well in terms of specific growth rate and survival rate. So it is unlikely that the escapees of GIFT from aquaculture systems would become established in the wild.	Wijenayake et al. (2008)
The CBD requirement of the recipient country to prevent the introduction or to control or eradicate alien species that threaten its ecosystems, habitats or species	There are cases where full compliance with the CBD has not been in place when GIFT has been used for aquaculture development, such as using GIFT for pond culture in a flood prone river basin in Sri Lanka.	Amaraweera et al. (2021)
	The receiving country should indicate the development objective it intends to achieve with the GIFT introduction.	Anthony and Richard (2016)
	Tilapia farming should follow more effective preventive measures throughout all processes, from enterprise establishment to processing the fish for consumption, and it is important to take measures to avoid the release or accidental escape of cultivated individuals at all fish farming stages.	Ortega et al. (2015)
	In Nigeria, aquaculture development has been driven by social and economic objectives, such as improving nutrition in rural areas, generating supplementary income, diversifying income activities and creating employment. Water bodies in Nigeria where the use of GIFT should be restricted or prevented to avoid ecological and environmental risks need to be identified through a national advisory team.	Kaleem and Sabi (2020)

Risk assessment framework consideration	Synopsis	References
Balancing ecological risks and economic gains	Measures to address possible adverse impacts of species introductions in inland waters should be undertaken by conducting a science-based risk assessment before introduction and balancing ecological risk and economic gains through valuation of ecosystem goods and services of inland water bodies.	Cuvin-Aralar (2016)
	GIFT's faster growth can yield significant increases in tilapia production in Asia. So it is believed that substantial improvements in aquaculture production in Africa can be achieved through GIFT aquaculture.	Acosta and Gupta (2010); Anash et al. (2014)
Potential to alleviate food insecurity, malnutrition and poverty	Nile tilapia makes up almost half (43.6%) of African aquaculture production. Much of the tilapia and catfish are semi-intensively produced, which requires additional feeding. There is considerable motivation to develop aquaculture in sub-Saharan Africa, including small-scale cage farming in large lakes as well as small-scale fish farming integrated into family agriculture systems.	AFD/EC/GIZ (2017)
Need for benefit sharing of GIFT R&D with African countries	Adopting the GIFT strain would benefit both producers and consumers in each of the countries where it is introduced. Africa supplied Nile tilapia genes for developing GIFT, which is a legitimate reason to share the benefits of GIFT R&D with African countries. If GIFT is not introduced into African countries, they might introduce other fish that could cause more damage to biodiversity and the environment. As such, there is no point keeping the strain away from Africa if the genetic improvement of tilapia or the introduction of any other genetically improved fish species is going to occur on the continent.	Acosta and Gupta (2010)
Sustaining tilapia aquaculture in Nigeria: Changing anti-tilapia attitudes	There are over 25 species of tilapia in Nigeria, out of which about six are used for aquaculture. To sustain tilapia aquaculture in the country, it is necessary that anti-tilapia attitudes, which are illogical, are changed, and that environmentally compatible enterprises, well integrated with other development initiatives, are introduced.	El-Sayed (2006); Fagbenro et al. (2010); Kaleem and Sabi (2020).
Better practices for tilapia farming and husbandry	Generally, tilapia farming does not pose adverse environmental impacts. However, as in all forms of fish farming, poor fish husbandry practices can contribute to water pollution and eutrophication. Good husbandry and environmentally friendly farming practices are therefore essential to minimize adverse environmental effects from tilapia farming.	Ansah et al. (2014)

Risk assessment framework consideration	Synopsis	References
Potential environmental risks associated with biosafety: • spread of diseases and parasites • adverse impacts on natural environments and their biodiversity through diseases and parasites and through predation and competition for food and spawning grounds • hybridization • habitat modification	Potential environmental risks through the spread of diseases and parasites are dealt with by another consultancy assignment.[11] First detection of TiLV infection was reported in farmed and wild Nile tilapia from Lake Victoria.	Mugimba et al. (2018)
	The development and dissemination of GIFT, GIFT-derived and other Nile tilapia have not caused any significant adverse impacts on existing aquaculture or on the natural environment and biodiversity in the Asia-Pacific, where there is rich freshwater biodiversity and habitats. As these biosafety issues are also relevant to Africa, introducing GIFT into Nigeria should be coupled with formulating and implementing appropriate policies, rules and regulations for environmental safeguards.	ADB (2005)
	In Sri Lanka, the lowering reproductive performance of *O. mossambicus* in reservoirs is evident due to hybridization with *O. niloticus*. Also, evidence has been found in Africa on hybridization of Nile tilapia with other *Oreochromis* species. In Nigeria, however, the only potentially reproductive compatible species with Nile tilapia is *O. aureus*, which was reported from Lake Kainji.	Welcomme (1967); Amarasinghe and De Silva (1996); Mwanja et al. (2001); Firmat et al. (2013); Firmat et al. (2013); Deines et al. (2014); FishBase (2021)
	There are two indirect environmental effects of GIFT in aquatic habitats: (i) turbidity in clear waters and a lower amount of available light in the water, which affects all organisms relying on photosynthesis and (ii) discharge of high nutrient excreta, which causes severe water pollution, such as high biochemical oxygen demand, elevated nitrogen, phosphate, and suspended solids. However, there are no proper scientific studies to confirm these impacts on the environment. To control the growth of blue-green algae in fishponds, 10 mg l-1 aluminium sulphate (alum) can be used without any negative effect on fish growth and water quality.	Dawah et al. (2015)
Habitats	The aquaculture industry in Nigeria is very promising, as there are water bodies, some institutional commitment and a high demand for fish. Nigeria has more than 260 medium and large dams, with a combined storage capacity above 30 billion m^3 of water. The dams could be used for cage and pen aquaculture.	Kaleem and Sabi (2020)
The presence of natural enemies, predators and competitors	*O. niloticus* is the only species that has managed to co-exist with the Nile perch in lakes Victoria and Kyoga. Nile perch is reported to occur in some lakes and reservoirs of Nigeria. *Clarias gariepinus* and *Heterobranchus longifilis* are used for population control of Nile tilapia aquaculture ponds. The hybrid clariid catfish, *H. longifilis* x *C. gariepinus* and *H. bidorsalis* x *C. gariepinus*, have high propensity for being piscivores. *C. gariepinus, H.s bidorsalis, H. bidorsalis/H. longifilis x C. gariepinus, Parachanna obscura, Hemichromis fasciatus* are potential predators of Nile tilapia in Nigeria.	Ita (1993); Balirwa (1998); Fagbenro (2000, 2002 and 2004); Offem et al. (2009); Limbu et al. (2015); Kaleem and Sabi (2020)
The presence of potentially reproductive compatible species	There are over 25 species of tilapia in Nigeria. Of these, *O. aureus* is the only native species and is a potentially reproductive compatible species with Nile tilapia.	Ita (1993); Teugels and van den Audenaerde (2003); Kaleem and Sabi (2020); FishBase (2021)

Table 2. Ecological and environmental risk assessment summary.

9. Recommendations

Ecological and environmental risk management measures that could be implemented pertaining to transferring GIFT from Malaysia to Nigeria are categorized under three sub-headings: before, during and after transfer.

Before transfer

1. TiLV has emerged as a significant viral disease of farmed Nile tilapia, with the potential to impede expansion of aquaculture production. The first detection of TiLV by PCR in farmed and wild Nile tilapia from Lake Victoria was reported by Mugimba et al. (2018). Any potential risk of bringing TiLV into Nigeria should be prevented. As such, appropriate policies, rules and regulations and implementation mechanisms should be in place for aquaculture development with long-term biosafety, quarantine and other environmental safeguards.[12]

2. In receiving transferred GIFT from Malaysia, Nigeria should strictly comply with the objectives of the CBD while addressing the development objectives. Aquaculture development in Nigeria has been driven by social and economic objectives. Because of this, introducing GIFT into Nigeria to increase aquaculture production could be considered an important strategy. Potential impacts on the environment should be avoided to prevent adverse impacts on the ecosystems, habitats or species. Water bodies in Nigeria where the use of GIFT should be restricted or prevented to avoid ecological and environmental risks have to be identified by an independent national advisory team.

During transfer

3. The transferred yolk sac fry will be kept in a designated land-based, secured quarantine facility in Nigeria's Ogun State. The regular health checks should be supplemented with occasional assessment of genetic resources to ensure genetic diversity is not being lost in subsequent generations. A monitoring program should be established in key areas where GIFT may enter Nigerian waters. Best aquaculture practices should be adopted with strong measures to prevent farmed fish from escaping. Monitoring the surrounding environment for GIFT will also be essential. Capacity building and awareness creation activities for key stakeholders will be necessary to reduce the risk of illegal transfer of GIFT and to increase awareness of GIFT in Nigeria.

4. The following enabling conditions must be in place in Nigeria for disseminating GIFT for its sustainability:[13]
   - the existence of a strong national institute, with adequate capabilities in fish genetics research
   - adequate resources and continued commitments for implementing national fish breeding programs
   - multilevel networks and broad-based partnerships, including those between private and public institutions, for production and distribution of genetically improved broodstock and seed
   - Market-driven demand for the farmed species concerned and for the prospects of gaining attractive returns from fish farming
   - supportive policies, facilities and infrastructure for fish farming
   - access by fish farmers to livelihood assets (human, social, natural, physical and financial capital) and to support services
   - enforcement of biosafety and environmental safeguards.

After transfer

5. The follow-up activity of WorldFish's program for introducing GIFT should be implemented to ensure long-term effectiveness of the breeding programs and to develop national strategies to effectively disseminate and maintain the improved strains.

6. It is recommended that GIFT farming follow more effective preventive measures throughout all processes, from enterprise establishment to processing the fish for

consumption. It is important to take measures to avoid the release or accidental escape of the cultivated individuals at all fish farming stages.

7. Adopting GIFT aquaculture would benefit both producers and consumers of fish in each country where it is introduced. According to Acosta and Gupta (2010), in many developing countries where GIFT is already available, the strain is responsible for increasing tilapia production from a wide range of farming systems and spreading the fish supply to a wide range of consumers, including the poor. Aquaculture development in Nigeria has been driven by social and economic objectives. As such, introducing GIFT to increase aquaculture production in Nigeria could be considered an important strategy.

It is recommended that policies are formulated and investments are promoted to fulfil the enabling conditions for sustained genetic improvement in aquaculture and to achieve sustained benefits for producers, intermediaries and consumers.

8. As in all forms of fish farming, poor fish husbandry practices can contribute to water pollution and eutrophication. It is essential to minimize adverse environmental effects from farming GIFT in Nigeria through good husbandry and environmentally friendly farming practices.

Photo credit: Trong Quoc Trinh/WorldFish

Improvised GIFT egg incubators (Myanmar).

Notes

1 http://www.fao.org/fishery/dias/en

2 http://www.fao.org/fishery/dias/en

3 http://www.fao.org/fishery/dias/en

4 https://cals.arizona.edu/azaqua/ata.html

5 https://rsis.ramsar.org/ris/1749

6 https://rsis.ramsar.org/ris/1039

7 https://rsis.ramsar.org/ris/1757

8 https://rsis.ramsar.org/ris/1759

9 https://www.aquanet.com/philippines-tilapia

10 https://www.cabi.org/isc/datasheet/72086

11 See also Arthur JR in press.

12 See also Arthur JR in press.

13 See also Bartley D in press.

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About WorldFish

WorldFish is a nonprofit research and innovation institution that creates, advances and translates scientific research on aquatic food systems into scalable solutions with transformational impact on human well-being and the environment. Our research data, evidence and insights shape better practices, policies and investment decisions for sustainable development in low- and middle-income countries.

We have a global presence across 20 countries in Asia, Africa and the Pacific with 460 staff of 30 nationalities deployed where the greatest sustainable development challenges can be addressed through holistic aquatic food systems solutions.

Our research and innovation work spans climate change, food security and nutrition, sustainable fisheries and aquaculture, the blue economy and ocean governance, One Health, genetics and AgriTech, and it integrates evidence and perspectives on gender, youth and social inclusion. Our approach empowers people for change over the long term: research excellence and engagement with national and international partners are at the heart of our efforts to set new agendas, build capacities and support better decision-making on the critical issues of our times.

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