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Cage farming in the environmental mix of Lake Victoria: An analysis of its status, potential environmental and ecological effects, and a call for sustainability

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Lake Victoria is the second largest freshwater lake in the world that was once a biodiversity hotspot hosting over 500 endemic haplochromine cichlids that were later decimated by exotic introductions and anthropogenically driven environmental and ecological changes. The environmental and ecological changes in the lake over the years have been attributed to overfishing, eutrophication, introduction of exotic species, pollution and possibly climate change. The lake's capture fishery, which is the main economic activity directly and indirectly supporting over 40 million people, has continued to decline after experiencing a boom between the 1970s and 1990s following the introduction of Nile Perch (Lates niloticus) *and Nile Tilapia* (Oreochromis niloticus). *In order to augment capture fisheries from the lake, cage culture was introduced in 2005, but its sustainability and influence on the ecology of the lake are not well understood. In this review, we examine the genesis of degradation of Lake Victoria and assess the role of cage culture as both a solution to the current situation and a cause for concern for the ecology of the lake. To compile this review, we utilized data in the grey and published literature. Studies show that the degradation of the lake can be traced back to the 1930s when the trophic status and ecology of the lake started showing signs of anthropogenic influence. The Nile Perch was introduced in early 1960s to replenish the fishery but its ecological impacts were felt in 1970s and 1980s when the native haplochromine species started to disappear from catches. Progressively, the ecological changes and management concerns in the lake have become a complex mix of exotic species introductions, eutrophication, and overfishing. In this mix of persistent ecological changes, the once thriving capture fisheries revolving around the two exotic species* (L. niloticus and O. niloticus) *have significantly declined threatening the livelihoods of millions of people directly and indirectly involved in the fisheries. These declines necessitated the introduction of cage culture in 2005 to fill the increasing demand for fish from the lake. Ever since, cage numbers have increased tremendously (>6 000 by 2020) and is now operated by over 60 different firms which are owned either individually or by groups. Over 70% of the cages have been installed in shallow areas within the Winam Gulf which goes against the guidelines on cage installation and operation; regulations on cage*

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farming were introduced after the activity had gained momentum in the lake. Limnological data in areas of the lake that have been stocked with cages has shown evidence of negative effects on water quality. This decline in water quality can be attributed to remnant feeds used in cages, of which 50% are the sinking types, and wastes from fish excretion and egestion. Although data are limited, the potential influence of cage farming on the already altered ecology and environment of Lake Victoria needs to be recognized and investigated. This study recommends studies targeting operations of cages in the lake, including a comprehensive environmental audit to inform their sustainability and relevant policy.

Keywords: aquaculture, capture fisheries, fisheries management, eutrophication, water pollution

Introduction

Lake Victoria is an important freshwater resource directly and indirectly supporting over 40 million people in the riparian countries of East Africa (Masese and McClain, 2012). It is only second to Lake Superior (North America) in terms of size, covering an area of 68,000 km^2, with a mean depth of 40 m. It is shared by the three East African countries with Tanzania having the lion's share (51%) followed by Uganda (43%) and Kenya at 6% of the surface area. The Winam Gulf in the Kenyan portion of the lake is shallower compared to the main lake in both Tanzania and Uganda. Rivers discharging into the lake drain a vast catchment of approximately 195,000 km^2 drawn from the East African countries including Rwanda and Burundi (Masese and McClain, 2012). The lake has a unique biodiversity from which provisioning, supporting, regulating and cultural benefits are derived. These goods and services are utilized not only by the riparian communities but also by the overseas markets where commercial fisheries' products are sold. It is the largest freshwater fishery in the world initially producing approximately one million tons of fish per year (Sitoki et al., 2010) but whose landings have drastically reduced to about 500,000 tons in the entire lake (Njiru et al., 2008) and to 118,145 tons from 180,000 tons on the Kenyan part of the lake (Aura et al., 2020). It offers employment opportunities, food and fetches income for the communities in the East African region. The main fishes of economic importance are the exotic Nile Perch (*Lates niloticus*) and Nile Tilapia (*Oreochromis niloticus*), and the endemic silver cyprinid (*Rastrineobola argentea)* locally known as Dagaa or Omena (Njiru et al., 2007, 2008). The fishery is both commercial and artisanal (Abila, 2000; Cowx, 2005; Njiru et al., 2008). It is one of the most productive fisheries in Kenya, earning the country over $US 600 million (Njiru et al., 2005), although fish production has significantly reduced (Aloo et al., 2017; Nyamweya et al., 2020). Nevertheless, the lake is a vital source of both industrial and domestic water supply (Njiru et al., 2008; Njiru et al., 2018).

Following the ecological changes and exotic species introductions (Hecky et al., 2010; Marshall, 2018), the lake has lost over 200 endemic species of haplochromine cichlids out of the 500 described by Witte et al. (1992a,b) and Witte et al. (2007). The ecological changes in the lake are correlated with human activities in catchments of major influent rivers (Verschuren et al., 2002; Nyakeya et al., 2018a, b; Nyakeya et al., 2017; Nyakeya, 2016; Gichana et al., 2014; Gichana et al.,2015; Mugidde et al., 2003). Specifically, the causes of the environmental degradation and ecological changes include overfishing, exotic introductions, nutrient loading, urbanization and industrialization and the subsequent discharge of untreated wastes into waterways that get their way into the lake (Scheren et al., 2001; Verschuren et al., 2002; Hecky et al., 2010; Nyamweya et al., 2020). Consequently, the fish catches from the lake have been declining and without proper management, the lake may fail to provide the benefits it once did to millions of people in this basin and beyond (Kayanda et al., 2017).

Several management interventions were introduced to improve fish production in the lake. These include banning of trawling and seining, use of gill nets of at least 4.5" mesh-size to minimize recruitment overfishing, introduction of closed seasons for fish breeding and reproduction and demarcation of breeding/nursery areas for fish protection (Kolding et al., 2014; Njiru et al., 2018). Paradoxically, little has been achieved, as evidenced by the continued decline in fish production, thus affecting riparian people's livelihoods (Njiru et al., 2010; Fiorella et al., 2014; Nyamweya et al., 2020). It is against this backdrop that people are investing in cage culture in the lake (Njiru et al., 2018; Nyamweya et al., 2020). However, there are concerns that cage culture may be a source of nutrients and organic matter from fish excretion and egestion, diseases and parasiticides and antibiotics used for disease control (Orina et al., 2018; Njiru et al., 2019). There is also a general concern on the sustainability of cage farming in the lake as a replacement for capture fisheries without compromising the status of an already modified ecosystem. These concerns are pertinent in view of continued dwindling fish stocks in the lake and other inland water in the region (Njiru et al., 2018; Masese et al., 2020; Walumona et al., 2022; Kondowe et al., 2022).

In this review, we place the ecological changes that have occurred in Lake Victoria into perspective by discussing the historical environmental degradation of the Kenyan part of the lake. We then examine the development of cage culture in the lake, its current status, socio-economic effects on people, and the possible ecological influences on the lake ecosystem. We also discuss challenges that cage culture is facing in the lake and offer potential mitigation measures that can make the practice more sustainable.

Data sources for this review

This review focuses on the genesis of degradation of Lake Victoria and whether the introduction of cage culture can revive the once vibrant fishery. To achieve this, sources of data used in the review included reviewing published literature in peer-reviewed journals accessed via different databases such as Web of Science, Directorate of Open Access Journals, Google Scholar, KMFRI Institutional Repository, and African Journals Online. Reports and unpublished institutional data from the State Department of Fisheries and Departments of Aquaculture and Blue Economy in the five riparian Kenyan Counties were also accessed. Although the bulk of the data reviewed were based on research conducted in Lake Victoria, other data sources from other tropical lakes, but with relevancy to the thematic area of the present study, were also used to enrich the review. These data also helped to shape the professional opinion expressed in this paper on the sustainable management of the lake and its fisheries amid the expanding cage culture. It is on this basis that sound management options for the lake are couched.

Historical perspective on environmental degradation of Lake Victoria

Eutrophication

Eutrophication is the enrichment of nutrients in the aquatic ecosystems leading to increased primary production. In Lake Victoria, eutrophication was witnessed in the 1930s in the inshore waters (Gichuki et al., 2006; Hecky et al., 2010). It was linked to increased farming activities and soil erosion in the catchments of major influent rivers that led to increased nutrient loading into the lake (Verschuren et al., 2002; Gichuki et al., 2006). Untreated municipal waste from the riparian cities/towns is also responsible for eutrophication in the lake as the construction of sewerage facilities for the treatment of municipal waste has not kept pace with the growing human population (Gichuki et al., 2006; Scheren et al., 2001; Ntiba et al., 2001).

Changes in phytoplankton communities have been reported in Lake Victoria as a result of eutrophication (Mugidde, 2003; Lung'ayia et al., 2001). As a result of increased nutrient loading, phytoplankton biomass increased tenfold from the levels in the 1930s to the 1990s while silica concentration decreased significantly (Kling et al., 2001; Hecky et al., 2010). The waters of the lake are now dominated by nitrogen fixing cyanobacteria that have substituted the once dominant diatoms, greens and blue-greens (Ochumba and Kibaara, 1989; Babu et al., 2015). Eutrophication has exacerbated the proliferation of invasive macrophytes in Lake Victoria, resulting in socio-economic and ecological issues (Opande et al., 2004; Villamagna and Murphy, 2009). Because of increased respiration of senescent algal mats and macrophytes, the concentration of dissolved oxygen in the hypolimnetic water has also declined (Lung'aiya et al., 2001; Hecky et al., 2010). Eutrophication is suspected to be behind occasional fish kills in Lake Victoria (Hecky et al., 1994). During seasonal water mixing, the deoxygenated or hypoxic hypolimnectic waters are brought to the surface causing death to sensitive fish species such as *L. niloticus* (Ochumba and Kibaara, 1989). Eutrophication may have also had an effect on the ecological shift in zooplankton communities in the lake. According to Mwebaza-Ndawula (1994) eutrophication induced competition between the herbivorous zooplankters, resulting in the disappearance of some species.

If unchecked, eutrophication will continue to have deleterious effects on the ecology and fisheries of Lake Victoria, including on public health and livestock in the riparian areas. Cyanobacterial blooms and microcystin poisoning through water and fish consumption have become a major concern (Simiyu et al., 2018; Roegner et al., 2020). Cases of stomach upsets and skin irritations have been also reported among people (Sitoki et al., 2012). There is a likelihood of water becoming unsuitable for domestic use in the coming years thus increasing treatment costs. Cyanobacterial blooms also pose ecological challenges to other organisms in the lake and the entire food web (Onyango et al., 2020; Olokotum et al., 2020).

Exotic and invasive species

In one of the earliest research expeditions in the lake in the late 1920s, the fishery of Lake Victoria comprised of many small and bony species of haplochromine cichlids (Graham, 1929). They were of no economic value in terms of a commercial fishery. Suggestions were made for the introduction of a predatory fish to prey on these bony fishes and convert them into bigger flesh for economic gains (Anderson, 1961). This was thought to be one of the most important steps towards improving the livelihoods of the fishing communities in the region. However, Graham (1929) warned of dire consequences in introducing a predatory fish into the lake.

In about three decades, Graham's (1929) advice was ignored and the introduction of *L. niloticus* in Lake Victoria was made (Marshall, 2018). In the 1980s, a change in species composition of the fishery with a sharp decline in haplochromines and an increase in *L. niloticus* was observed. Out of 500,000 mt of fish catches that were recorded in 1989, 70% were *L. niloticus* (Sitoki et al., 2010). Consequently, an ecological shift was evident in the lake and currently the fishery is dominated by three fish species; *O. niloticus*, *L. niloticus* and *R. argentea* (Njiru et al., 2018; Nyamweya et al., 2020).

The introduction of *L. niloticus* and the subsequent decimation of hundreds of haplochromine cichlids triggered a trophic cascade that led to changes in the zooplankton composition and ecology in the lake (Verschuren et al., 2002; Hecky et al., 2010; Nyakeya et al., 2020a; Ogello et al., 2013). As *L. niloticus* preyed on the haplochromines reducing their diversity and abundance, *R. argentea*, which was the major prey item for most haplochromine species, thrived and exerted more pressure on cladocerans and calanoids (Mavuti and Litterick, 1991; Mwebaza-Ndawula, 1994). The resultant trophic cascades intensified predation pressure on the large herbivorous zooplankton (Gophen et al., 1995). For example, the calanoids that were abundant (47%) in the lake in the 1930s reduced to about 30% by the 1960s and by the year 2000, its composition was below 2% (Ogello et al., 2013). A similar trend is observed for cladocerans whereby in the 1930s, they were made up of 39% composition, which declined to 30% in the 1960s and then disappeared completely by the year 2000 (Figure 1) (Worthington, 1931; Mwebaza-Ndawula, 1994; Mwambungu, 2004; Ogello et al., 2013). On the contrary, increased predation on large-bodied zooplankton by *R. argentea*, cyclopoids that were least dominant in the lake in 1930s (<2%), became the most abundant (Figure 1), dominating by more than 80% by the year 2000 (Nyakeya et al., 2020a).

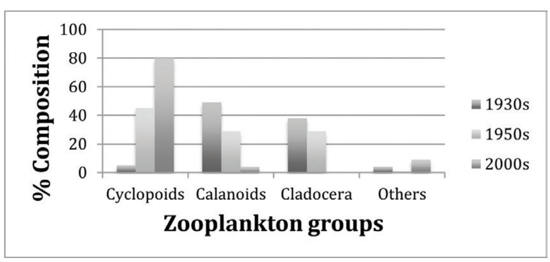

Figure 1. A shift in the composition (%) of zooplankton groups in Lake Victoria between 1930s and 1990s. Source: Ogello et al. (2013)

The water hyacinth *Eichhornia crassipes* (Mart., Solms) is another invasive species that has caused a lot of havoc in the lake ecosystem.

E. crassipes is reported to have been introduced upstream of River Kagera in the 1940s and was reported on the Kenyan part of Lake Victoria in the early 1990s (Gichuki et al., 2012). It has since spread to the entire lake despite numerous trials to eradicate it using both biological and mechanical means (Ongore et al., 2018), and its effects have been felt socially, economically and ecologically (Nyamweya et al., 2016). The extensive mats deprive the water of enough sunlight for primary production resulting in hypoxic conditions developing which can cause fish kills (Taabu-Munyaho et al., 2016). Once it dies off nutrients return into the system through decomposition (Ongore et al., 2018). Generation of hydropower and abstraction of water for irrigation and domestic use have also been affected by massive growth and proliferation of water hyacinth and algal blooms (Opande et al., 2004; Roegner et al., 2020).

The introduction of *E. crassipes* has been reported to be responsible for the disappearance of other macrophyte species such as *Azolla nilotica* and *Trapa natans* from some parts of the lake (Ongore et al., 2018). At the same time, its proliferation has caused a resurgence of hippograss (*Vossia cuspidata* Roxb. Griff.) in the lake. Although *E. crassipes* can be of benefit, its negative impacts outweigh its benefits. According to Kateregga and Sterner (2009) it is an important breeding ground for *Clarias gariepinus* and *Protopterus aethiopicus*, which were reportedly disappearing from the lake because of limited habitats for the juveniles. It is also a nursery ground for the *L. niloticus* fry (Njiru et al., 2007). The proliferation of *E. crassipes* has also been linked to the resurgence of haplochromine cichlids in the lake. This is attributed to the refuge offered by the dense mats of *E. crassipes* that are inaccessible to the predatory *L. niloticus* (Balirwa et al., 2003; Kishe-Machumu et al., 2012, 2015). Unlike other lakes (e.g. Lake Baringo) that are deficient of nutrients (Nyakeya et al., 2018c), *E. crassipes* in Lake Victoria flourishes because of increased intensive agricultural activities in the catchments of influent rivers and urbanization that are major sources of nutrient loading into the lake (Nyenje et al., 2010; Njiru et al., 2014; van Soesbergen et al., 2019; Achieng et al., 2021).

The introduction of *O. niloticus,* which is considered aggressive and invasive fish species, saw the decimation of the endemic *O. variabilis*, and *O. esculentus* by utilizing each and every niche at the expense of the native species (Njiru et al., 2004). The disappearance of these native tilapiines has also been associated with hybridization, overcrowding, as well as the introduction of parasites and diseases (Trewavas, 1983; Ogutu-Ohwayo, 1990). Hybridization is caused by high water turbidity associated with algal blooms and siltation, which made visual selection of mating partners difficult (Njiru, 2007).

Introduction of cage fish farming in Lake Victoria

History and current status of cage culture in Lake Victoria

Fish farming in cages in lakes in Kenya has expanded rapidly since its introduction in Lake Victoria (Aura et al., 2018; Njiru et al., 2018). The first trials were conducted in 1988 by the Lake Basin Development Authority (LBDA) in Lake Victoria at Dunga Beach, Kisumu but failed (Aura et al., 2018). With rapid decline in fish catches in the lake, Dominion Farms Limited in Siaya County successfully installed cages in their ponds in 2005. Some trials were also made by a European Union (EU) funded project, 'BOMOSA' in Small Water Bodies (SWBs) within the Lake Victoria Basin in 2007 (Munguti et al., 2014). The success of this project led the Dunga Fishermen Co-operative Society to install cages in Lake Victoria at Dunga Beach, Kisumu in 2009 (Aura et al., 2018).

Beach Management Units (BMUs) in Kisumu and Siaya Counties got into commercial cage culture in 2012 that was supported by the Association for Strengthening Agriculture Research in East and Central Africa (ASARECA). This did not succeed because of lack of capacity in deploying and managing the cages (Aura et al., 2018). However, since 2013 cage culture in Lake Victoria has witnessed tremendous growth. Currently, there are over 6,000 cages installed in the Kenyan waters of the lake for the production of *O. niloticus.* By the year 2018, there were over 3 million individuals of *O. niloticus* stocked at an average density of 350 individuals/m^3 (Njiru et al., 2019). The cages are of different sizes ranging from the small sizes (2.0 m^3), medium size (2.5 m – 5.0 m x 2.0 m x 2.0 m) and large size (10.5 m x 5.0 m x 2.5 m) (Aura et al., 2018). Small sizes of cages are preferred because of their affordability in terms of construction and management (Njiru et al., 2019).

Currently, there are over 60 investors involved in cage fish farming in Lake Victoria (Figure 2) of which many are individually owned (Aura et al., 2018) while about 37% are group-owned (Njiru et al., 2019). Cage fish farming has supplemented fish production from capture fisheries in the lake with a total of 12,000 mt of fish produced per cycle of about 8 months a year in 2018 (Njiru et al., 2019). The value of cage raised fish was $12 million. With the introduction of cage fish farming in the lake, there is a clear manifestation of job creation either directly and indirectly along the value chain with a contribution to enhancement of the Blue Economy Concept (BEC) (Aura et al., 2018).

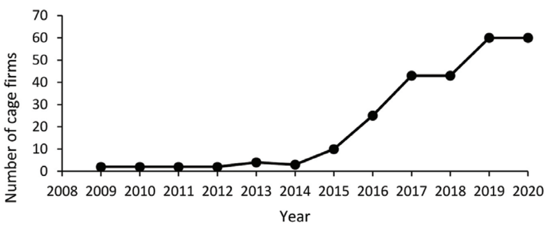

Figure 2. Growth in the number of fish cage enterprises from the year 2008 to 2020.

Cage fish farming in Lake Victoria provides a good opportunity for the realization of the Kenya government's strategy to fight poverty and malnutrition through job creation in fish farming and support sectors such as manufacturing, transport and marketing. In the manufacturing sector, large quantities of commercially formulated feeds are required to feed millions of fish in the cages. The number of local fish-feed producers has increased as a result, with 50% of the feeds being manufactured locally (Aura et al., 2018).

Sustainability of cage culture in Lake Victoria

Lake Victoria is known as one of the biodiversity hotspots in the world, but this accolade has been lost due to massive extinction of more than 200 haplochromine cichlids following ecological changes and the introduction of *L. niloticus* into the lake (Marshall, 2018; Nyamweya et al., 2020). The ecological changes that have been witnessed due to pollution and eutrophication (Sitoki et al., 2010; Hecky et al., 2010) are transient, and can get worse if efforts are not put in place to address the causes. For instance, nutrient loading from the catchments, municipal effluent discharges and non-point sources of pollution from farmlands and urban centers can all increase as human population grows, more forested land is converted into grazing areas and settlements, including urbanization, and more industries are being built without concomitant waste handling mechanisms (Scheren et al., 2001; Verschuren et al., 2002; Nyenje et al., 2010; Masese et al., 2012). Lake Victoria is now classified as eutrophic with some parts being hypereutrophic especially the Winam Gulf (Musinguzi et al., 2019).

With the introduction and expansion of cage farming in the lake, additional nutrients and organic matter from feeds may exacerbate the eutrophic status of the lake. This is because cages are already installed along the shorelines where eutrophication is more pronounced (Njiru et al., 2019) against the recently published guidelines by LVFO (2018), which are yet to be incorporated into guidelines for management of cage fish farming in Kenya. Given the already eutrophic conditions in the lake, there is concern whether cage farming is a sustainable method of fish production. It is against this backdrop that we discuss potential effects posed by cage fish farming in the lake in spite of the evident benefits that are accruing from it, including job creation, poverty eradication, food security and increased trade (Aura et al., 2018). The potential negative effects of cage farming in the lake are discussed below.

Pollution

Lake Victoria has undergone through trophic transitions over the years from an oligotrophic status in the early 1930s to its current eutrophic status (Nyakeya et al., 2009; Hecky et al., 2010; Musinguzi et al., 2019). Eutrophication is one of the major environmental challenges cited as the cause of occasional fish kills and biodiversity loss in the lake (Nyakeya et al., 2022; Njiru et al., 2008). Eutrophication has changed the composition of phytoplankton from a dominance of diatoms to cyanobacteria, which has resulted in the production of cyanotoxins that can cause human health disorders (Sitoki et al., 2012). The activities responsible for nutrient enrichment in the lake include extensive agricultural activities in the catchments, urbanization, industrial and municipal effluents and wastewater disposal (Scheren et al., 2001; Verschuren et al., 2002; Gichana et al.,2014; Nyakeya et al., 2018a, b).

Cage culture might introduce more pollutants into the lake, such as nutrients and organic matter from feeds, parasiticides and antibiotics for disease management and other wastes from people involved in cage farming. The commonly utilized feeds for aquaculture in Kenya fall into three categories namely floating; floating and sinking; and sinking (Opiyo et al., 2018). Of these feed types, the sinking type comprises 50 % of feeds used in cages in the lake, whereas the floating and sinking feeds comprise 37.5 % and the floating type 12.5 %.

Because consumption of feeds by fish in cages is not 100%, there are always possibilities of feeds sinking to the bottom of the lake. It is documented that less than 30% of feeds are digested and absorbed by fish for metabolic requirements and growth (Gichana, 2019; Gichana et al., 2019a, b; Gichana et al., 2018; Troell, 1996). The remaining are excreted as non-faecal or faecal losses into the aquatic environment (Schram et al., 2014; Gichana et al., 2019a,b). Non-faecal losses consist of metabolites of digested feeds that are not retained for growth but excreted as ammonia and urea, while faecal losses constitute the main solid wastes from aquaculture systems that can be major sources of nutrients (phosphorus and nitrogen) when they leach and are mineralized. The solid faecal wastes can also add to the amount of suspended solids in water (Meriac et al., 2014). Accumulation of nutrient-rich wastes in the sediments and the water column can exacerbate the problem of eutrophication in the lake. Lake sediments can be re-suspended during upwelling and cause internal loading of nutrients. Decomposition of suspended organic matter can deplete dissolved oxygen also in the water column and be detrimental to fish and other aquatic life. Re-suspended organic matter and nutrients, especially ammonia and nitrates, can cause fish poisoning and fish kills, not only in the wild but also in cages. Fish kills, especially *L. niloticus*, is a common occurrence in the Kenyan part of Lake Victoria (Ochumba, 1990), a condition that can be worsened by additional loading of nutrients and organic matter from the cages. The latest fish kills in the lake, which was attributed to upwelling, occurred in January 2021 in Kenya (Kenya: Why Lake Victoria Fish Are Dying - allAfrica.com) and the rest of the lake (Ugandans warned not to eat dead fish washed ashore - BBC News). Fishes such as L. niloticus may be displaced and continue to decline in catches owing to their high demand for oxygen (>5 mg/L) (Njiru et al., 2019).

Organic matter in the form of faecal losses from fish in cages are rich in nitrogen (N) and phosphorus (P) (Meriac et al., 2014). Estimates indicate that 132.5 kg of N and 25.0 kg of P are released into water for every 1000 kg of fish production in cages (Islam, 2005). Furthermore, mass balance studies in cage culture systems estimate that about 24 % of carbon (C), 31 % of N and 31 % of P added into cages as feeds are harvested as fish biomass (Holby and Hall, 1991; Hall et al., 1990, 1992). In Lake Malawi, nutrient losses from cages to the lake accounted for between 81 – 91 % for C, 80 % for N and 85 – 92 % for P (Gondwe et al., 2011). The current fish production estimates from cages in Lake Victoria (~12,000 mt) per production cycle (8 months) (Njiru et al, 2019) correspond to nearly 1,600 mt of N and 300 mt of P. According to Neto et al. (2015) for every mt of Tilapia production in cage culture, 11.041 mt of organic matter are discharged into the aquatic environment. Out of this, 0.045 mt of nitrogen and 0.014 mt of phosphorus are produced. In Lake Victoria, this will translate into 12,487.56 mt of organic matter, 539.4 mt of nitrogen and 171.12 mt of phosphorus input into the lake every 8 months.

With the projected increase in cage fish farming in Lake Victoria in the coming years, loading of organic matter and nutrients into the lake will increase proportionally (Egesa, 2018). In a long-term study on the impacts of salmon cage culture in the United States, Brooks and Mahnken (2003) reported major impacts of organic waste including chemical changes in the sediments and seabed deterioration. The potential environmental impacts posed by cage farming in Lake Victoria might be more pronounced on the Kenyan part of the lake because it is more confined (the Nyanza Gulf) and shallower than the rest of the lake (Hamilton et al., 2020). Although there are guidelines on cage location, and depth is one of the considerations (Aura et al., 2018), sometimes fish farmers flout them and locate cages in shallow areas. The shallower Kenyan part of Lake Victoria is already facing serious environmental challenges mainly from land-based anthropogenic activities (Mwamburi et al., 2020). Poor water quality has already been cited as an issue of great concern around areas with cages (Musinguzi et al., 2019; Orina et al., 2018; Longgen et al., 2009). Cage culture, therefore, has been identified as a potential threat to the ecological integrity of Lake Victoria and as an emerging environmental issue that may negatively influence capture fisheries and water provision for residents living along the shores of the lake (Mwamburi et al., 2020). It is therefore important that guidelines on cage fish farming are adhered to with continuous monitoring as part of sustainable management of the lake (Kundu et al., 2017).

Fish diseases

Cage fish farming is an intensively managed enterprise which limits the movement of fish. The cage culture environment tends to create overcrowding due to high stocking densities. This increases the host proximity and enhances the ability of parasites to locate their hosts (Morton et al., 2005). This creates conditions that are favourable for disease outbreaks and high prevalence of parasites. Caged fish have a low probability of avoiding parasitic infections from schools of fish already infected because of the confinement (Barber et al., 2000).

The environment surrounding cages is often rich in nutrients favouring saprophytic, bacterial and fungi growth if hygiene is not properly maintained. Once fish in the cages are infected with parasites, transmission can occur to fish in the wild (Morton et al., 2005). Severe cases of cestode (*Triaenophorus nodulosus* and *Diphyllobothrium* spp.) infestation in caged fish whereby infection spreads from wild fish has been reported (Jarrams et al., 1980). Some parasitic infections can be transmitted from fish in cages to wild fish populations (Morton et al., 2005). Mardones et al. (2013) reported the spread of infectious salmon anaemia virus (ISAV) from caged Atlantic salmon (*Salmo salar*) in Chile. The cage structure also serves as a substrate for several organisms and thus the predominance of algal blooms. Clogging of the holding net can cause rapid growth of other organisms and can create temporary stagnation of water (FAO, 2015) and low biological oxygen demand (BOD) resulting in a conglomeration of pathogenic organisms that cause dropsy conditions, gill and fin rot. Prevalent pathogenic organisms that have been reported in these conditions include fungi, *Saprolegnia, Achlya*, bacteria, *Pseudomonas, Aeromonas*, Protozoa and *Costia* (FAO, 2015).

In Lake Victoria, more than 50% of the cages have reported the occurrence of fish diseases and parasites (Aura et al., 2018). The most prevalent disease observed is fin rot, which was attributed to poor water quality and management practices (Aura et al., 2018). If unchecked, cages that were thought to boost fish production may cause more harm in terms of fish kills not only inside cages but in the adjacent environment. Good fish husbandry at all times is paramount in cages (Ofori et al., 2009).

Conflicts

Cage culture in Lake Victoria is unregulated, hence cages are sometimes installed in unsuitable sites. According to Njiru et al. (2019) over 70 % of cages already established in the lake are located in shallow areas demarcated as breeding grounds for wild fish. With the increased number of fishermen (currently 14,000), the Kenyan part of the lake is overcrowded (Njiru et al., 2019). This has already caused conflicts among cage farmers and fishers in the lake (Personal observation).

A ministerial ban by the Kenya government on deployment of more cages in the lake was issued in September 2020 (https://www.standardmedia.co.ke/business/article/2001387031/protests-over-ban-on-fish-cages-in-lake). The statement noted that there were no policy guidelines on cage farming in the lake to guide the industry. As a result, many of the cages (76 %) are deployed in either eutrophic, hypereutrophic or shallow areas along the shoreline (Njiru et al., 2019; Musinguzi et al., 2019) raising concerns on their potential environmental impact. The riparian County governments in Kenya may see such a suspension as a means of denying people a source of income and employment. Conflicts in terms of the management of fisheries resources already exist between the two levels of government (i.e. National vs County governments) (Nyakeya et al., 2020b). The banning of installation of more cages in the lake may, therefore, face resistance by the five riparian County governments in Kenya. The suspension has also caused tension among farmers whose cages are already deployed in non-suitable sites (Personal observation). Although they have been requested to redeploy their cages following the developed guidelines (LVFO, 2018), they have resisted due to the high costs involved. From the onset, the Kenyan government failed to offer proper guidelines on cage culture in the lake hence redirecting farmers to reinstall their cages in suitably identified areas has become a challenge. This scenario could have been avoided if relevant government agencies had carried out an environmental impact assessment (EIA) before cage farming was commissioned as a commercial venture in the lake as provided for in the Environmental Management and Coordination Act (EMCA, 1999).

Hybridization of cultured fish with wild fish

Fish breeds of unknown sources stocked in the cages can escape and interbreed with the wild fish populations. These can cause genetic divergence through admixture and hybridization with the wild fish stocks (Rothuis et al., 2014). Loss of native *O. esculentus* in Lake Victoria (Angienda et al. 2014) *and O. mossambicus* in South Africa (Zengeya et al., 2015) due to hybridization has been documented. Hybridization of *O. niloticus* and the native *O. macrochir* and *O. andersonii* has also been reported in the Kafue River, Zambia (Deines et al., 2014). Recent geometric, morphometric and molecular genetic analyses with respect to *O. niloticus* in Lake Victoria reported morphological and genetic variation because of hybridization of wild fish stocks and translocated fish populations from different aquaculture facilities (Tibihika et al., 2020). The recent boom of cage culture may worsen hybridization of the wild fish populations with cage cultured escapees of unknown genetic constitution in Lake Victoria. In view of this concern, agreed standard operating procedures ought to be developed to ensure that authenticated and certified hatcheries supply fingerlings to cage operators in the lake. Should such mechanisms fail, then there is a likelihood of interfering with the wild fish gene pool which may further imperil the declining capture fisheries in the lake.

Poor water quality

Lake Victoria is a major source of water for millions of people in cities and villages on the shores of the lake and beyond. With enriched nutrients, and frequent outbreaks on algal blooms in inshore areas around the lake, water quality for domestic and industrial use is increasingly in doubt (Aura et al., 2021; Sitoki et al., 2012). The problem is being compounded by additional nutrients from cage farming. Studies have recorded low levels of DO (< 3 mg/L) in cages (Aura et al., 2018; Njiru et al., 2019). These low levels are linked to the high densities of fish stocked in cages and decomposing food remains in an already eutrophic environment (Njiru et al., 2019). Other water quality parameters that have deteriorated in cages as compared to the surrounding environment include BOD with a mean of 2.8 mg/L, total ammonia (NH_3^+-N) recording a mean of 24.8 µg/L (Aura et al., 2018). In addition, P levels have recorded an increase, with a mean of 45.8 µg/L in the environment around cages (Aura et al., 2018). In another study in the Napoleon Gulf in Uganda, cages have been found to change the composition and diversity of benthic macroinvertebrates, with a decrease in the density of Mollusca and the poor water quality sensitive Ephemeroptera, Plecoptera and Trichoptera, and an increase in the density of oligochaetes (Egesa et al., 2018). General pollution and poor water quality are likely to be exacerbated by cage farming in the lake if sound management practices are not embraced.

Management implications from this review

Degradation of Lake Victoria is a sad chapter in the history of the lake which has manifested itself in the form of environmental and ecological changes including, amongst others, the upsurge of the introduced predatory *L. niloticus* (Goudswaard et al., 2008), the loss of many haplochromine species (Witte et al., 1992a,b), eutrophication (Hecky et al., 2010), decrease in dissolved oxygen concentration (Hecky et al., 1994; Wanink et al., 2001) and water transparency (Witte et al., 2005) and changes in the composition of aquatic communities (Wanink, 1999; Balirwa et al., 2003; Goudswaard et al., 2006). While causes of these environmental and ecological changes have been identified, there has been very little success in managing them, at least as evidenced by the deterioration in water quality and declining fish catches in recent years (Kayanda et al., 2017; Nyamweya et al., 2020). Studies have also reported increased rates of land use and land cover changes in the catchments of many rivers, with increasing acreage of agricultural and grazing land at the expense of native forests, grasslands and shrublands (Mati et al., 2008; Masese et al., 2012; Gichana et al., 2015; Mugo et al., 2020).

Although the lake was once a lucrative source of livelihoods supporting millions of people in its basin and beyond, recent evidence indicate that these livelihoods are unraveling in many fronts, with the sustainability of goods and services deriving from the lake at a great risk of being lost. Water for domestic use is of poorer quality than ever before because of contamination by cyanotoxins from algal blooms. Fish kills due to anoxic and hypoxic conditions still continue to be experienced and the capture fishery has significantly declined. In response to the declining fish catches, cage culture was introduced in the lake to fill the enormous demand for fish. This has noticeably come with a lot of benefits, including boosting the blue economy, increasing food security, job creation, income generation, among others. There is a likelihood that fish production from cages will continue to increase to meet the increasing demand from the growing human population. Although data are limited, emerging evidence shows that cage culture is already compounding the environmental challenges the lake is experiencing.

Whereas the lake has shown considerable resilience to environmental degradation, it is not clear how it will respond to additional loading of nutrients and organic matter from cage farming facilities. This raises concern on the potential of cage culture to provide a sustainable source of fish while maintaining other services deriving from the lake to people in its basin and beyond. Accordingly, we recommend extensive and long term studies on the effects posed by cage farming on the ecology of the lake, with a focus on water quality, eutrophication, hybridization of native tilapiines and the diversity and composition of aquatic communities (phytoplankton, zooplankton and macroinvertebrates). An intensive environmental audit is also needed to determine the suitability of cage culture in Lake Victoria and how well it can be managed for sustainability. This will form the basis for site selection for cage installation.

Although there exists policy guidelines on cage culture in Lake Victoria, these came after many farmers had installed their cages. This is a failure on the part of relevant regulatory agencies to offer guidance before the introduction of cage farming in the lake. There are ample provisions in the law to guide any development project in Kenya (EMCA, 1999), but it seems that adequate environmental impact assessment studies were not undertaken before cage culture was allowed to be carried out in the lake. In the meantime, continuous monitoring of water quality (physical, chemical and biological) should be instituted in areas of the lake where cages are installed to provide data for decision making. For the sustainability of cage farming, it is imperative to determine fish carrying capacity of Lake Victoria so as to avoid overstocking. There is also a need to undertake spatial planning of the lake to help identify suitable sites for installing cages and where possible redeploy cages that are in shallow waters. To address the problem unsuitable location of cages, recommendations should be made to install cages in deep areas of the lake and avoid the shallow areas that are also used by fish for breeding. There is no documented data on the use of hormones among caged fish hence the need for further studies on this. Further, we recommend a detailed study on sewerage input into the lake vis-à-vis the fish feeds that end up in the lake to inform management. Similarly, floating fish feeds should be used exclusively to feed caged fish to reduce sinking of feeds that foul the benthic environment. The feed should be highly digestible with a high feed conversion efficiency, and feeding schedules should be adopted that enhance feed intake and retention of nutrients from the feeds.

Conclusions

Lake Victoria has undergone a series of ecological changes over the last century. The lake was once a diverse oligotrophic ecosystem with a complex food web, but has been converted by human activities into a eutrophic ecosystem dominated by a limited number of fish species. The once vibrant fishery has also gone through a series of changes and is now dominated by three species of which *L. niloticus* and *O. niloticus* catches are in a steep decline. Cage farming was largely introduced to safeguard fish production and livelihoods of fisher folk around the lake. However, rearing of fish in cages is highly dependent on the use of commercially formulated feeds and sometimes the use of parasiticides and antibiotics for disease control. What is not known is how the introduced feeds and chemicals are managed so as not to compromise further the already modified ecology conditions in the lake. Although studies on the effects of cage farming on water quality and ecology of the Lake Victoria are limited, data available shows that water quality around the cages is compromised with reduced dissolved oxygen concentrations, increased concentrations of nitrates and ammonia. It is therefore important that the environmental and ecological impacts posed by cage farming in the lake are recognized so that appropriate strategies are put in place for the sustainability. These measures should include proper site selection and management of feeds and chemicals used in cages, and proper selection of fish species and hybrids reared in the cages.

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