International Journal of Biosciences | IJB |
ISSN: 2220-6655 (Print), 2222-5234 (Online)
http://www.innspub.net
Vol. 17, No. 4, p. 1-31, 2020

INNSPUB

REVIEW PAPER OPEN ACCESS

# Prospects for aquaculture development in Africa in the context of a changing climate: a review

**Frida Nyamete[1*], Musa Chacha[1], Titus Msagati[2], Jofrey Raymond[1]**

[1]*Department of Food Biotechnology and Nutritional Sciences, The Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania*

[2]*College of Science Engineering and Technology, Roodepoort, Johannesburg, 1709, South Africa*

**Key words:** Climate-smart aquaculture, Climate change, Context-specific model, Africa, Food security.

http://dx.doi.org/10.12692/ijb/17.4.1-31 Article published on October 10, 2020

## Abstract

In Africa, aquaculture has contributed to global fish production over the past decade, supporting rising fish demand and improving incomes and food security of the growing populations in the region. However, there are significant concerns for the health of aquatic resources due to the increasing impacts of climate change and climate variability. Aquaculture in Africa also faces increasing constraints as competition from the agricultural sector for the available resources intensifies, significantly impacting location, productivity, and scalability of the sector's production systems. The contributions of the aquaculture sector to global emissions of greenhouse gases are discussed. We recognize that ecosystems are generally complex; therefore, we have provided region-specific and local context-specific, climate-smart aquaculture solutions required to enable sustainable growth of the sector. This review paper is a reminder of the effects of climate change impacts on the vulnerable aquaculture-dependent economies and communities in Africa. It also provides a framework of strategic climate-smart aquaculture (CSA) approaches for the sector to (a) sustainably increase output productivity and efficiency; (b) reduce vulnerability and increase resilience, and (c) mitigate greenhouse gas emissions in fisheries and aquaculture. In Africa, climate-smart success will depend on country-specific biophysical, socio-economic dynamics, institutional and market capacity, regional geopolitics, and local needs and interests. To enhance resilience, increase efficiency, and avoid maladaptation of the proposed CSA approaches, African governments should integrate their national climate change policies and aquaculture programs with broader development objectives such as food security, sustainability, biodiversity, social equity, and stability.

* **Corresponding Author:** Frida Nyamete ✉ nachep@yahoo.com

## Introduction

Globally, aquaculture has become the predominant source of fish protein (Golden *et al.,* 2017), doubling its production every decade for the past 50 years (Bostock and Seixas, 2015). In Africa, aquaculture has contributed immensely to the total amount of fish produced over the past decade, supporting rising fish demand and improving incomes, food and nutrition security of the growing populations in the region (Mwima *et al.,* 2012). The level of fish consumption in Africa during 2015–2017 was 9.9 kg but it's projected to decline to 9.6 kg by 2027 and ultimately to 7.7 kg by 2050 despite the steady population growth (OECD, 2018; Chan *et al.,* 2019) and increasing demand for fish (Kobayashi *et al.*, 2015). East African region, second only to Southern Asia, had the highest food insecure population in 2016, compared to the rest of the world (AUC-NEPAD, 2014a; FAO, 2018d). As such, Africa is projected to continue heavily relying on imported frozen fish due to its ease of availability, steady supply, and price to meet the demand gap and its nutritional needs (OECD, 2018; Tran *et al.,* 2019). As revealed by IMPACT Model projections, Africa's total fish output will be significantly low in the next decade because of the expected slow growth of capture fisheries and aquaculture in the region (Chan *et al.,* 2019).

More than 200 million people in Africa are reportedly regular fish consumers (Béné and Heck, 2005), especially tilapia—the most commonly cultured fish species in the region (De San, 2013). The top aquaculture producers in Africa are Egypt (~1.37 million tonnes) and Nigeria (~ 306,727 tonnes) (FAO, 2018a), mostly driven by increased investment by the private and public sector interventions as the continent strives to achieve food and nutrition secure nations (Mwima *et al.*, 2012). The Food and Agriculture Organization (FAO) estimates that fish accounts for more than 20 percent of animal protein supplies in about 20 African countries (FAO, 2017a). The sector is now rapidly responding to this market demand for fish with an average annual growth rate of 21 percent in Sub-Saharan Africa alone (Satia, 2017), especially in Ghana, Kenya, Nigeria, South Africa, Uganda, and Zambia (Asiedu *et al.*, 2015; Kaminski *et al.*, 2017; Satia, 2017).

Climate change and climate variability have the greatest impact on fisheries and aquaculture sector in Africa, especially on productivity and sustainability. Unfortunately, since the impact of climate change varies by region; it could likely worsen food insecurity in Africa as a whole by disrupting the distribution of available resources in the continent's aquatic environments (Challinor *et al.*, 2007). It's projected that by 2050 if the current production and consumption trends in Africa continue, more than half of the fish consumed in Africa will be imported (Chan *et al.*, 2019). Hence, sustainable climate-smart growth of the aquaculture sector in Africa is required to meet the demand of an increasingly growing population.

Around 1.74 million tonnes of global aquaculture production comes from Africa, contributing about 2 percent of total global production. Nile perch (43.6 percent), African catfish (11.9%), and common carp (10.5%) are some of the most commonly consumed fish species in Africa (James, 2018). However, the growth and development of the aquaculture sector in Africa still require more effort to ensure the consistent production of safe and nutritious fish as well as smart aquaculture practices for a sustainable future (James, 2018). Indeed, a recent study on impacts of climate variability and adaptation options in Africa found that Egypt and Nigeria, two countries with high fish consumption per capita, were relatively vulnerable to the effects of climate change including temperature (Adeleke *et al.,* 2018).

Fish produced can be for domestic consumption, export trade, or both. Inland aquaculture is dominated by small-scale fish farmers, mainly for subsistence and to satisfy the growing local markets. Subsequently, a supply response has been observed in some countries such as Zambia whereby medium to large scale farms have begun to upgrade operations to increase their aquaculture output (Tweddle *et al.*, 2015; Kaminski *et al.*, 2017). Indeed, Zambia has recently emerged as the largest producer of farmed fish in the Southern African Development Community (SADC) region (Genschick *et al.,* 2017), while Kenya is the fourth in the whole of Africa, having grown exponentially to peak its fish production at 24,096 tonnes in 2014, driven largely by an ambitious Economic Stimulus Programme (ESP) aquaculture subsidy programme commissioned from 2009–2013 (KNBS, 2018; Obiero *et al.,* 2019c). The ESP focused on critical aquacultural infrastructures such as pond design and construction, fish feeds, fingerlings supply, as well as post-harvest management and human resource institution to assist fish farmers (Obiero *et al.,* 2019c).

Despite these incredible interventions to prioritize the development of the sector in Africa, subsistence fish farming has limited supervision from veterinarians and extension officers in the region. Sadly, consumer protection control and other regulations and legislations are not fully enforced in the aquaculture sector in some of the African countries (Rutaisire *et al.*, 2009) which increases the likelihood of contamination from harmful compounds such as antibiotics, heavy metals and pesticides from anthropogenic sources (Wamala *et al.*, 2018; Kostich & Lazorchak, 2008; Burridge *et al.*, 2010; Nnodum *et al.*, 2018; Mark *et al.*, 2019). Country-specific monitoring programmes are in place to monitor such contamination to ensure food safety. However, such monitoring cannot completely prevent or eliminate the supply of contaminated aquaculture products to consumers.

Integrated fish farming, that is, using animal waste and excreta to supplement fish feed in ponds, is still the most commonly practiced form of aquaculture system (Elsaidy *et al.*, 2015). Of course, this disregards the importance of human health protection by intentionally introducing pathogenic microorganisms into the aquaculture facility which could lead to food-borne illnesses. Therefore, there is a need to establish a more suitable aquaculture system to ensure safety or the protection of public health. A range of actions is required to make aquaculture system climate-smart considering the effect of climate change on food security, especially on the African economies that often have a low capacity to adapt to change.

More importantly, one of the biggest concerns is how climate-induced changes in productivity and availability of aquatic resources have led to the expansion of capture fisheries and commercial aquaculture to meet the growing market demand for fish and contributed to the increasing carbon imprint into the atmosphere. As such, a shift to local context-specific, climate-smart aquaculture strategies is required to enable the sector to prepare for a sustainable future, especially through the development of climate-resilient and low-carbon capture fisheries and aquaculture systems. Therefore, this review highlights the prospects for climate-smart aquaculture development in Africa considering climate change impacts on aquatic systems and more broadly, the potential reduction of vulnerability within the communities that depend on fisheries and aquaculture.

*Climate-related changes that affect ecological functions*

Climate-related changes include physical and chemical processes known to increase greenhouse gas emissions, much of which is absorbed by aquatic systems, leading to substantial changes in aquatic ecosystems (FAO, 2016b). The devastating effects of climate change and climate variability on aquatic environments include changes in the abundance and distribution of fisheries resources and the overall suitability of some regions for aquaculture systems (FAO, 2016a). This impacts their ability to provide food security and livelihoods to populations dependent on aquaculture (Kareko *et al.,* 2011; FAO, 2016b). Effects of climate change on aquaculture systems include changes in salinity and freshwater content, oxygen concentration, water acidification and temperature, storm systems, rainfall and river flows (Cochrane *et al.*, 2009; FAO, 2016b). Oceans and coastal areas are particularly vulnerable to these changes (FAO, 2016b). For example, changes in carbon chemistry can affect shell development in marine shellfish whereas temperature changes can increase the sensitivity of some species to pathogens (FAO, 2016b).

Productivity potential and species distribution in aquaculture systems dependent on inland water bodies such as dams, rivers, and lakes may be affected by extreme weather events including changes in air and water temperatures as well as levels of precipitation (IPPC, 2014; FAO, 2016b). Climate change may also have significant stress on post-harvest activities. For instance, the availability of adequate water for processing may be challenging, especially if the same water source is required for other farming practices such as irrigation. Of course, climate-induced changes often occur simultaneously and their effects are cumulative, thus their impact on natural resources, food security, and social stability is huge (IPPC, 2014).

The growing demand for fish and other aquatic products in Africa Worldwide, aquaculture as well as marine and freshwater-capture fisheries have contributed to the growth of fish production to meet the global demand, rising from 19 million metric tonnes (MT) in 1950 to 171 million MT in 2016 (FAO, 2018b). Fish is the most accessible and affordable source of animal protein, especially for 'poor' socioeconomic classes (Béné *et al.*, 2015). Fish production is crucial for over 3 billion people in developing countries since fish contribute 17% of animal protein and 7% of all proteins consumed (FAO, 2018b).

In Africa, many factors drive fish preferences and consumption including affordability (average of US$2/kg), rising population growth, increasing income levels, accessibility, as well as awareness of health benefits and the nutritional value of fish (Githukia *et al.*, 2014; Darko *et al.*, 2016). Nutritionally, fish provides docosahexaenoic and eicosapentaenoic omega-3 fatty acids, high-quality essential amino acids, minerals, and vitamins, which are necessary for improved health (Kris-Etherton *et al.*, 2002; Beveridge *et al.*, 2013; Béné *et al.*, 2015; Golden *et al.*, 2016). As such, fish is a high-value food that supports the nutritional wellbeing of poor communities (Beveridge *et al.*, 2013; Béné *et al.*, 2015; Golden *et al.*, 2016; FAO, 2017b;) considering that several African countries have significant numbers of undernourished and malnourished populations (FAO, 2018c; FAO, 2018d). For instance, the high malnutrition incidences in the East African region, especially in Ethiopia, Kenya, Tanzania, and Uganda, has been shown to correspond to the significantly lower quantity of fish consumed/capita (average of 5.3 kgs) compared to the rest of Africa (10.1 kg), and global level of 19.8 kg (Cai and Leung, 2017; Obiero *et al.*, 2019).

Roughly 200 million people in Africa consume fish as the main animal protein source and micronutrition (AUC-NEPAD, 2014b). Africa's population is expected to double by 2050 (UN-DESA, 2017), but unfortunately, the continent's contribution to the amount of fish produced, consumed, and traded globally is so small. In 2016, for example, the aquaculture sector only contributed about 2.5% of global fish production (FAO, 2018b). Thus, with overfishing and overexploitation in the capture fisheries sector (FAO, 2018b), aquaculture is expected to meet the increased fish demand in Africa (Chan *et al.*, 2019), and continue supplying animal protein to the poor and food-insecure populations (Kobayashi *et al.*, 2015; Golden *et al.*, 2017).

Rising urbanization, increased incomes, and awareness of the health benefits associated with consuming fish have contributed largely to the increased global fish consumption rates (Anderson *et al.,* 2017). Capture fisheries and aquaculture resources have improved the economic security of farmers through domestic and international trade of wild and farmed fish, employment, and other livelihood support services (De Graaf and Garibaldi, 2014; Cai *et al.,* 2019). Global capture fisheries production peaked in 1996 at around 96 million MT, whereas aquaculture production has continued to grow for the past 50 years to produce 80 million MT of fish in 2016 (FAO, 2018b). As such, aquaculture alone is on-trend to produce 195 MT of fish by 2027 and contribute immensely to the future expansion of fish as food (OECD-FAO, 2018). No doubt, the increasing demand for fish in Africa and the ongoing transformations in fish supply have led to the gradual growth and development of aquaculture in the continent (Kobayashi *et al.,* 2015), bringing an estimated US$3 billion annually (De Graaf and Garibaldi, 2014). The New Partnership for Africa's Development (NEPAD) estimates that about 1.6 million tonnes of fishery production in Africa come from aquaculture (AUC-NEPAD 2014b). The sector also employs about 12.3 million people in the areas of fishing, processing, equipment manufacturing, and fish farming (De Graaf and Garibaldi, 2014), generating about 1.26% of gross domestic product (GDP) (AUC-NEPAD, 2014b).

The growth of fish production in Africa is not immune to problems as competition for land, water, energy, and feed resources intensifies. Combined with the potential impacts of climate change on ecosystems, the aquaculture sector faces significant challenges as it tries to satisfy the gap between capture fisheries. This paper reviews current information on the extent to which aquaculture contributes to food and nutrition security in Africa, and highlights a need for developing targeted policies and investment in climate-smart approaches to meet the 21st century socio-economic and environmental challenges impacting the region. Of course, the future of fish demand in Africa opens up opportunities for investments in aquaculture value chains. This, however, is strongly linked to both population and economic growth of the continent (Kassam and Dorward, 2017).

*Aquaculture practices in Africa and its challenges*

Aquaculture in Africa is dominated by men. This is probably due to strong cultural norms that explicitly define men as heads of households and women as caretakers of chores in the homestead (Akrofi, 2002). However, women's roles in aquaculture production activities are significant, ranging from processing and transportation to marketing and sale (Akrofi, 2002; Kruijssen *et al.,* 2018).

Aquaculture accounts for 17% of total fish production in Africa (FAO, 2018b; Chan *et al.,* 2019; Obiero *et al.,* 2019a). Fish and fisheries products in Africa mostly come from two production techniques, namely aquaculture and wild-catch. In general, there are three types of aquaculture practiced around the world, namely, land-based commercial, water-based commercial, and small-scale production. These production techniques use different sets of inputs. For instance, the aquaculture sectors use five types of inputs, namely, seed, feed, labor, fuel, and sector-specific inputs such as capital investment in the facility. On the other hand, wild-catch (capture fisheries) sectors only use labor, fuel, and other sector-specific inputs. Regardless of the production techniques, there is evidence that climate-related changes such as rising temperature and flooding of waterways affect the ecological functions of the aquatic environments and impact overall yield. Flooding, for instance, may introduce pollutants from sewage into the ponds, thereby reducing dissolved oxygen levels and destroying the fish as a result of algal bloom (Weatherdon *et al*., 2016).

Generally, aquaculture sector in Africa has expanded its production capacity to include other mariculture species (Oyinlola *et al.,* 2018) through innovation and intensification of production systems (Joffre *et al.,* 2017), adoption of new technologies (Kumar *et al.,* 2018) and improvement in resource efficiency and utilization (Waite *et al.,* 2014). Indeed, studies indicate that the aquaculture sector has generally benefited from the adoption of new technologies in aquaculture production, breeding systems, nutrition and feed formulations, genetic selection programs, labor-saving equipment, development of vaccines, investment in management practices as well as improved regulatory frameworks and control (Joffre *et al.,* 2017; Kumar *et al.,* 2018). Despite the recent growth in Africa's aquaculture sector, the industry isn't technologically advanced and is largely constrained by lack of good-quality seed and feed, poor market access and value addition, lack of credit/capital, insufficient extension services, and programs, poor management systems, low capacity in disease diagnostics, training and biosecurity, and disadvantageous competition from cheaper imported fish products from established markets such as China (Mwima *et al.,* 2012; Kaminski *et al.,* 2017), thus its full potential in contributing to the sustainable food supply in the region is unknown (Brummett *et al.,* 2008; Obiero *et al.,* 2019c).

Like in other animal production systems, feed is the most expensive input in aquaculture. In Africa, most farmers prefer to use farm-made feeds formulated with grains (Amankwah *et al.,* 2016) either alone or with animal waste and excreta as a supplemental nutrient source, mainly to benefit from the synergistic effects of inter-related farm activities and off-set high production cost (Petersen *et al.*, 2002; Elsaidy *et al.*, 2015). Commercially manufactured feeds, either locally-made or imported, are often used by larger aquaculture operators with access to sufficient credit and markets, and often can tolerate risks associated with declining prices. The fish feeds are mostly sourced from privately- or government-owned hatcheries (Opiyo *et al.*, 2018) and small-scale semi-commercial feed manufacturers (Obiero *et al.,* 2019b). However, the cost of high quality imported fish feeds is often beyond the budget of many small-scale fish farmers, to the extent that some of the farmers would switch to risk management strategy to stabilize their incomes or abandon production altogether to minimize losses when production cost increases or competition with increasing fish imports become unsustainable.

Unfortunately, the fish feed sector has an unreliable supply chain, lacks proper quality monitoring and standards management strategy, compromising on production performance, consistency, and food safety (Obiero *et al.,* 2019b). Nevertheless, several other factors play an important role in determining the actual production capacity of a fish farm and its sustainability. These include but are not limited to (a) technological shift that reduces the environmental impacts of aquaculture (Troell *et al.,* 2009); (b) the diversification strategies to maximize on space and input (Rapsomanikis, 2015); (c) quality of governance and access to advisory and extension support services (Kuehne *et al.,* 2017); and (d) promotion and adoption of sustainable aquaculture practices (Engle, 2017; Kumar *et al.,* 2018). Some of these are either unavailable or inaccessible to many small- and large-scale fish producers and traders in Africa, suggesting that investments by the private sector are critical to sustain innovation, increase growth, improve production efficiency, and reduce production costs to stay in business.

*The role of aquaculture in greenhouse gas emissions*

The major greenhouse gases (GHGs) associated with aquaculture production are: (a) nitrous oxide ($N_2O$), emitted as a result of the microbial nitrification and denitrification of nitrogenous compounds in the ponds (e.g. fertilizers, manures, uneaten feed and excreted N), (b) carbon dioxide ($CO_2$), from energy and fuel consumption associated with farm management such as pumping water, lighting and powering vehicles, (c) methane ($CH_4$), arising during fish farm waste management, and (d) fluorinated gases (F-gases) leaking from cooling systems used on and off the farm (MacLeod *et al.,* 2019).

The application of feeds in aquaculture is the leading contributing factor in greenhouse gases (GHG) emission in the sector (Naylor *et al.*, 2000). Aquafeeds increase nutrient loadings in the water bodies and pond sediments in feed-based aquaculture production systems (Boyd *et al.,* 2010; Chatvijitkul *et al.,* 2017). Approximately 75 percent of the nitrogen consumed by fish from the feeds is excreted into the water as ammonia, while the remainder is converted into biomass (Hu *et al.,* 2012). Additionally, the carbon from the feeds can be transformed into carbon dioxide and methane by animals and microbes in the water (Boyd and Tucker, 2014) while a great amount of unconsumed feed become deposited in the pond sediments together with feces (Boyd *et al.,* 2010), where they continue to provide carbon for submerged macrophytes (Yuan *et al.,* 2019). Approximately 39.9

million tons of aquafeeds were used in global aquaculture in 2016 alone, leading to about 10.9 teragram carbon and 1.82 teragrams nitrogen discharged into the environment (Alltech, 2017).

Today, it is estimated that >40% of worldwide aquaculture production is carried out in earthen ponds around the world (Yuan *et al.,* 2019), contributing about 80.3% of the total methane emitted into the environment (Hu *et al.,* 2014). Since intensified systems with continuous aeration reportedly have the least emissions (Hu *et al.,* 2014), global adoption of aerated systems has been proposed to mitigate the significant rises in methane emissions from aquaculture sources (Yuan *et al.,* 2019).

It has also been suggested that pond sediments can sequestrate carbon and contribute to mitigation (Boyd *et al.,* 2010), which had previously been shown to complicate quantification of greenhouse gas emission (Verdegem and Bosma, 2009). However, later studies such as the Sustaining Ethical Aquaculture Trade (SEAT) project determined that it was impossible to quantify the extent by which pond sediments can act as carbon sinks due to uncertainties over the sequestration rates and stability of the carbon storage (Henriksson *et al.,* 2014).

Fertilizers are used in inland aquaculture systems to stimulate phytoplankton production for supplemental nutrients for the fish (Green, 2015). However, such anthropogenic use of fertilizers has the potential to significantly increase methane and nitrous oxide emissions from aquaculture systems into the environment. For instance, in 2008 alone, a global nitrous oxide emission from the aquaculture sector was estimated as 0.08 teragram (Williams and Crutzen, 2010). Using the nitrous oxide emissions factor of influent nitrogen ($EF_N$ = 1.80%) in sludge and wastewater treatment processes (Ahn *et al.,* 2010), nitrous oxide emission was later projected to increase to 0.60 teragrams by 2030 and account for 5.72% of global anthropogenic nitrous oxide emissions (Hu *et al.,* 2012).

Overall, approximately 0.45 percent of global anthropogenic greenhouse gas emissions in 2013 came from aquaculture sources, which is similar to the emission intensity from sheep production in the same period (MacLeod *et al.,* 2019). The modest emissions are large because fish have low feed conversion rate compared to terrestrial animals (Gjedrem *et al.,* 2012), do not produce methane via enteric fermentation (Hu *et al.,* 2012; MacLeod *et al.,* 2019), and lastly, their high fertility rate reduces breeding overhead (MacLeod *et al.,* 2019). These are three key determinants of fish emission intensity, considering that the greatest greenhouse gases in aquaculture come from aquafeeds (MacLeod *et al.,* 2019). Furthermore, unlike terrestrial mammals, fish (both finfish and shellfish) require less energy for physiological functions and excrete ammonia directly (MacLeod *et al.,* 2019). In aquaculture, shrimps and prawns have the highest emission intensity because they require energy usage for water aeration through the systems. On the other hand, bivalves have the lowest emission intensity since they source food from their environment and thus have no synthetic feed-related emissions (MacLeod *et al.,* 2019).

However, despite the low emissions from the sector, the contribution of aquaculture to the increasing global carbon footprint cannot be ignored. For example, carbon dioxide emission from energy usage in the post-harvesting and value addition activities such as drying, smoking, cold storage, and transportation, which are not included in the 0.45 percent, also has significant global warming potential. Additionally, aquafeed production use machines and equipment that require energy to grind and mix the raw materials or make and dry the pellets. The total energy used depends on local energy source and production efficiencies. The feed materials can be marine or terrestrial in origin and are often formulated to meet the nutritional needs of the fish depending on species and age. Poor feed quality may reduce fish performance and increase greenhouse gas emissions. Of course, the feed must eventually be transported to the farms for use, which requires energy utilization. Therefore, operations and processes that require high amounts of fuel and energy are among the highest greenhouse gas emitters.

*Climate change and its potential impacts on aquaculture systems in Africa*

Food production systems are especially vulnerable to the impacts of climate change and associated risks (Handisyde *et al.,* 2017). As such, there's urgent need to effectively respond to the threat of climate change, through mitigation and progressive adaptation strategies. On a global scale, climate change effects on the aquaculture and fisheries sector will lead to significant changes in the availability and trade of fish products, and for countries whose economies rely on this sector, create other geopolitical tensions (Barange *et al.,* 2018). In general, climate change is expected to affect fish and ecosystems, livelihoods, trade, and economies (Daw *et al.,* 2008; Allison *et al.,* 2009; Badjeck *et al.,* 2010; Brander, 2010). According to greenhouse gas emission scenario RCP8.5, global marine catch potential is projected to decrease by 7.0 – 12.1 percent by 2050, resulting in shifts in the availability and distribution of species (Barange *et al.,* 2018). As such, adaptations to climate change, including institutional adaptations, are necessary and must consider the multifaceted nature of aquaculture and fisheries.

Freshwater is a valuable resource and is used in many sectors of human life ranging from human consumption to agriculture, aquaculture, and recreation. Unfortunately, climate change is projected to result in a significant reduction in freshwater resources (Jimenez Cisneros, *et al.,* 2014). Competition for scarce freshwater resources seriously affects the sustainability of inland aquaculture and fisheries and adds stress to the already resource-stretched sector (Katikiro and Macusi, 2012). Today, Morocco is one of the African countries currently facing high stresses and is projected to become even dire in the future, while Papua New Guinea, the Congo, the Central African Republic and Gabon are under low stress at present and are projected to remain as such in the future (Barange *et al.,* 2018).

Physical and ecological impacts of climate change on global aquaculture and capture fisheries is well documented in the literature (Allison *et al.,* 2005; Handisyde *et al.,* 2006; Allison *et al.,* 2007; Daw *et al.,* 2008; Allison *et al.,* 2009; Barange and Perry, 2009). In general, the implications of climate change on aquaculture systems in individual countries and communities depend on their adaptive capacity (Aswani *et al.,* 2018). Climate change impacts on aquaculture may include losses of production, infrastructure, fish markets, or decreased safety of fishers at sea (Katikiro and Macusi, 2012; Barange *et al.,* 2018). For instance, the impact of precipitation on inland freshwater ecosystems has a significant effect on the supply and quality of freshwater lakes and rivers that support inland aquaculture and fisheries (Barange *et al.,* 2018).

Aquaculture systems are especially vulnerable to rising global temperatures, particularly production infrastructures in the tropics, where population densities are high (De Silva and Soto, 2009). In the last decade alone, global warming has produced weather events that were exceedingly rapid and extreme and differed from those of the past, adding more stress to the environment and aquatic systems and leading to changes to relative abundance, distribution and productivity of fish in the water bodies (Cheung *et al.,* 2010). Changes in sea temperature are ultimately responsible for other impacts such as acidification, sea-level rise, increased frequency and intensity of storms, extreme winds, flooding and erosion (De Silva and Sotto, 2009; Barange *et al.,* 2018), which may radically change the whole ecosystems and hence directly impact aquaculture-dependent communities and damage aquaculture infrastructure (Allison *et al.,* 2005). Furthermore, any losses to important coastal habitats such as mangroves ecosystem which support numerous fish species (IPCC, 2007) as a result of climate change could lead to disruption of fishing patterns and behavior (Katikiro and Macusi, 2012).

In Africa, both marine and inland water bodies such as wetlands, floodplains, lakes, and rivers are all susceptible to climate change effects, especially precipitation and rising temperature (FAO, 2010a; Settele *et al.,* 2014). Of course, increase precipitation lead to the expansion of fish habitats, and fishers would be expected to adapt to new systems and fishing range to maximize success (Barange *et al.,* 2018). However, increased precipitation may also lead to extreme events such as floods which may introduce contaminants and pathogens via surface runoffs into ponds and waterways. Low precipitation or prolonged drought had a profound effect on Nigeria's aquaculture systems supported by Lake Chad and was feared could lead to the total collapse of fishery activities in the West African nation (Oyebande *et al.,* 2002; FAO 2010a). Generally, reduced precipitation leads to increased competition for freshwater. Reduced levels of rainfall in inland catchments over time may make farmers in the agriculture sector to take on fishing to support their livelihoods (Katikiro and Macusi, 2012). On the other hand, increased precipitation in wetland and inland aquaculture systems may cause changes to the salinity of the water bodies, which could impact the survival of salinity-sensitive aquatic organisms including prawns (Katikiro and Macusi, 2012). In Africa, Uganda, Nigeria, and Egypt are estimated to be the most vulnerable to climate change (Barange *et al.,* 2018).

**Table 1.** A proposed framework for context-specific climate-smart aquaculture (CSA) in Africa: sustainably increasing output productivity and efficiency.

| Theme | Component | Climate Smart Priority Actions | Context and challenges | Potential Climate Change Impacts | Opportunities and Benefits | Outcome | References |
|---|---|---|---|---|---|---|---|
| Sustainably increasing output productivity and efficiency | Increase intensification to ensure economically sustainable productivity. | Aquaponics / Hydroponics | • Extractive aquaculture that contributes towards removing nutrients and organic loads.<br>• Bacteria metabolize the fish waste, and plants/vegetables assimilate the resulting nutrient-rich effluent through their rooting system.<br>• The purified water is then returned to the fish tanks.<br>• The financial investment for inputs required.<br>• Expert assessment and consultation required. | • Reduces watershed pollution caused by aquaculture effluent discharge.<br>• Potential to deliver higher yields of produce and protein with less labour and land.<br>• Uses a fraction of the water.<br>• No need for fertilizers and pesticides.<br>• High feed efficiency.<br>• Lower energy expenditure as there is no need to till the soil. | • Overcomes agricultural challenges such as shortages of freshwater, soil degradation, erosion, and mineral fertilizer requirement.<br>• Resilient; can be adapted to diverse and changing conditions.<br>• Combines a high level of biosecurity with a low risk of disease and external contamination. | • Increases food security by increasing agri-aquacultural productivity and incomes.<br>• Unlocks financial potential and supports socio-economic growth.<br>• Capitalize on synergies in the use of resources.<br>• Diversified production. | Martins *et al.*, 2010<br>FAO, 2013<br>FAO, 2014<br>Somerville *et al.*, 2014<br>FAO, 2016a<br>Chomo and Seggel, 2017<br>Barange *et al.*, 2018 |
| | Selective breeding and genetic improvements. | Breed for improved feed conversion ratio (FCR) | • Reduce FCR while selecting for increasing body size in fish. | • Selective breeding for strains efficient in using plant feed, especially for species at higher trophic levels.<br>• Use of species more efficient at using the feed, especially at lower trophic levels.<br>• Improve the physical performance of fish and reduce greenhouse gas emissions. | • Improves stocks.<br>• Make feeding more efficient.<br>• Reduces losses from disease. | • Need for species adapted to integrated farming and/or agroecological farming. | Troell *et al.*, 2009<br>Gjedrem *et al.*, 2012<br>Thoa *et al.*, 2016<br>Kumar *et al.*, 2016<br>Omasaki *et al.*, 2017 |

Increasingly wet conditions also put at risk the traditional food processing techniques such as the drying of fish (IPCC, 2014). Moreover, incidences of food-borne illnesses, such as ciguatera fish poisoning, and other types of diseases, are likely to increase as a result of climate change (IPCC, 2014). Increased flooding may also cause displacement of communities, subsequent migration and/or conflict, and destruction of aquaculture infrastructure, thus small-scale fishers in countries that over-depend on aquaculture and fisheries are most likely to suffer the consequences of climate change (Barange *et al.,* 2014; FAO, 2015).

Changing water temperatures and associated phonologies affect fish physiological processes and their ecological fitness (Brander, 2007; Barange and Perry, 2009; IPPC, 2014). It has been observed that most fish species sensitivity to acidification and pathogens increases in habitats beyond their thermal ranges (FAO, 2016b). Therefore, short-term climate change impacts on aquaculture and fisheries systems can include increased risks of pathogens and parasites, arising from rising global temperatures that affect their growth, metabolism, and ability to fight pathogens and diseases (Allison *et al.,* 2007; Ficke *et al.,* 2007). Long-term impacts can include prolonged drought and a decline in aquaculture and fisheries production. At worse, climate-driven changes in global temperature, precipitation levels, ocean acidification, changed monsoon cycles, sea-level rise, the length and frequency of hypoxia events, modified ocean circulation patterns, and the modified hydrological regimes (De Silva and Sotto, 2009; Katikiro and Macusi, 2012) are expected to have long-term impacts in the aquaculture sector to varying magnitudes (Barange *et al.,* 2018).

In Africa, Egypt's brackish water production and Madagascar's marine aquaculture are considered to be highly vulnerable to climate change (Handisyde *et al.,* 2017; Barange *et al.,* 2018). In the case of brackish water production, Senegal, Côte d'Ivoire, Tanzania, Madagascar, and Papua New Guinea are the countries with the lowest adaptive capacity to cope with the impacts of climate change; while for marine aquaculture, Mozambique, Madagascar, Senegal, and Papua New Guinea were found to have the particularly low adaptive capacity (Handisyde *et al.,* 2017; Barange *et al.,* 2018).

In the past, fishing communities in Africa have been able to cope with the rare weather events such as flooding by being geographically mobile and creating alternative livelihoods (Boko *et al.,* 2007). However, today, progressive adaptation strategies and resilience building are required since increasing population growth and administrative barriers make age-old tactics inapplicable. Of course, small-scale and artisanal fisheries and fishers are particularly vulnerable to the impacts of climate change (Barange *et al.,* 2018). They often consist of commercial boat-based, or a small-scale, beach-based line- and net-fishery, which are labor-intensive and mainly exploit the species in estuaries and near-shore waters (Barange *et al.,* 2018). Therefore, the adaptation options provided in the FAO guidelines (FAO, 2012; FAO, 2015) are particularly designed for this cohort and could be useful for promoting sustainable aquaculture development in Africa. Additionally, community-based approaches to fisheries governance would be essential in improving the economic stability of small-scale fishers in the region, considering the increasing likelihood of extreme weather incidences in the decades to come (Barange *et al.,* 2018).

Lastly, the impacts of climate change do not respect administrative borders, even though each country has unique risks and vulnerabilities as well as institutional and socio-economic differences. Inevitably, climate-induced implications on marine stock availability, distributions, and assemblage (Barange and Perry, 2009) can lead to transboundary conflict at both regional and international levels (Barange *et al.,* 2018). Many species could migrate towards deeper ocean waters to find their ideal habitat conditions such as temperature and oxygen levels. Some commercial species may migrate offshore, further away from traditional fishing grounds (IPCC, 2007), permitting other species that are tolerant of higher temperatures and changes in the salinity of coastal waters to move into the void (Roy *et al.,* 2007; FAO, 2016b), negatively impacting fishery and profitability (Fairweather *et al.,* 2006). In Africa, the impacts of climate change are of greatest concern in the South Western region, especially the fishing communities that depend on coastal and inland fisheries due to the high exposure of the low-latitude regions to the impacts of global warming (Barange *et al.,* 2014) and limited capacity to adapt to associated risks and opportunities (IPCC, 2014).

**Table 2.** A proposed framework for context-specific climate-smart aquaculture (CSA) in Africa: reducing vulnerability and increasing resilience.

| Theme | Component | Climate Smart Priority Actions | Context and challenges | Potential Climate Change Impacts | Opportunities and Benefits | Outcome | References |
|---|---|---|---|---|---|---|---|
| Reducing vulnerability and increasing resilience | Build climate-inclusive resilience. | Culture-based aquaculture | • Less costly, environmentally friendly food production system.<br>• Effective use of water resources.<br>• Increases diversification for food.<br>• System is vulnerable to the unpredictability of precipitation.<br>• Yields are much less than in most intensive aquaculture practices. | • Does not consume external feed resources.<br>• No greenhouse gas emission related to feed. | • Suitable for semi-intensive to extensive aquaculture systems.<br>• Stocking during the rainy season, and harvest at the onset of the dry season.<br>• Indigenous fish species from well-managed broodstock helps avoid genetic introgression. | • Increases food fish production and food security among rural communities that often share communal waterbodies.<br>• Improves the efficacy of water usage. | De Silva, 2003<br>Amarasinghe and Nguyen, 2009<br>FAO, 2013<br>FAO, 2016a<br>Barange *et al.,* 2018 |
| | Strengthen integrated adaptation to risk reduction. | Rice-fish system<br>• Integrated production systems. | • Diversification of resources and incomes.<br>• Maximizes food production and energy utilization, sustainably.<br>• Rearing fish in rice paddies to maximize food production and energy utilization sustainably. | • Increases efficiency in the use of resources.<br>• Mitigates greenhouse gas emissions from rice fields. | • Increases productivity and efficiency in the aquatic systems without compromising the nutritional quality and safety of the fish. | • Lead to stronger and more resilient communities. | De Silva and Soto, 2009<br>FAO, 2014<br>Lipper *et al.,* 2017<br>Barange *et al.,* 2018 |
| | Enhance resilience to climate change and disasters. | Improved pond design<br>• Use tarpaulin ponds during dry weather.<br>• Erect shades over the pond to reduce evaporation losses.<br>• Raised banks prevent the influx of floodwater.<br>• Use indoor ponds and Recirculating Aquaculture Systems (RAS) with water filtration mechanisms. | • Flooding may introduce pollutants from sewage and surface runoffs into the ponds, thereby reducing dissolved oxygen levels and destroying the fish as a result of algal bloom.<br>• Drought may reduce the availability or reliability of freshwater supplies in many places already subject to water scarcity.<br>• Increased risk of diseases, parasites, and harmful algal blooms during rainy seasons. | • Reduces vulnerability to long-term climate change impacts. | • Better water management to maintain aquacultural productivity, support food security, and nutrition.<br>• Boosts resilience through the uptake of improved freshwater utilization technologies.<br>• Invest in stronger facilities.<br>• Development of contingency plans. | • Better management to reduce stress.<br>• Increased monitoring for water quality, disease outbreaks, etc.<br>• Effective biosecurity plans that emphasize prevention are possible. | Daw *et al.,* 2009<br>De Silva and Soto, 2009<br>FAO, 2010b<br>Thaddeus *et al.,* 2012<br>Cattermoul *et al.,* 2014<br>FAO 2017d |

*Climate-smart approaches in aquaculture systems and their challenges*

FAO's ecosystem-based climate-smart approaches in aquaculture and fisheries consider (a) sustainable increase in productivity and efficiency, considering environmental and socio-economic aspects of the sector, (b) reducing vulnerability and increasing resilience to enable the sector to cope with impacts of climate change, and (c) mitigating greenhouse gases throughout the entire value chain. The suggested climate-smart approaches capable of achieving these objectives are the Ecosystem Approach to Fisheries

(EAF) and the Ecosystem Approach to Aquaculture (EAA) (FAO, 2016a).

According to FAO, some of the benefits of implementing the ecosystem approach to fisheries and aquaculture include (a) improving the general resilience of fisheries and aquaculture systems, including promoting the consumption of a greater diversity of fish species, to minimize vulnerability to the impacts of climate change and climate variability on resources, (b) adoption of context-specific and community-based adaptation strategies, and (c) stabilization of income for communities that rely on capture fisheries and aquaculture for their livelihoods (FAO, 2016a; Chomo and Seggel, 2017).

*(a) Sustainably increasing productivity and efficiency in aquaculture*

For aquaculture, fully integrated systems, proper watershed management, water planning, improved feed efficiency, better disease diagnosis, and treatment can help increase productivity and efficiency in the aquatic systems (De Silva and Soto, 2009; Troell *et al.,* 2014a), without compromising the nutritional quality and safety of the fish (Beveridge *et al.,* 2013). Some developed economies use innovative technologies such as hyperspectral imaging (HSI) to check diseases and microbial contamination in fish products (Vejarano *et al.,* 2017). Additionally, emerging biotechnologies such as the development of transgenic fish, for example, salmon in the United States and Canada (Aerni *et al.*, 2004) have enabled the production of fish with greater tolerance to temperature, salinity, and susceptibility to disease (Wakchaure *et al.,* 2015).

In terms of feed formulation, the aquaculture sector has been over-reliant on fishmeal and fish oil (Tacon and Metian, 2008); this has significantly constrained growth in the sector (Little *et al.,* 2016). Other constraints include increased competition from the agricultural sector for the available land and water resources (Troell *et al.,* 2014b), which could significantly impact location, productivity, and scalability of the aquaculture production systems (FAO and World Bank, 2015). As such, aquaponics (the symbiotic relationship between aquaculture and hydroponics) has been suggested as a potential climate-smart option for increasing efficiency and address these constraints (Martins *et al.*, 2010). Of course, hydroponics (the cultivation of plants in water without soil) can be combined with aquaculture in a closed recirculation system. The roots of the plants (or crops) floating on water can assimilate the nutrients metabolized by the bacteria, and then the purified water is often returned to the tanks/ponds for fish to use (FAO, 2016a; Chomo and Seggel, 2017).

Therefore, aquaponics (integrated agriculture/aquaculture technique) is a climate-smart approach for increasing productivity and efficiency in food production (FAO, 2016a).

The utilization of plants and vegetables in aquaponics helps minimize fish waste discharge and reduces watershed pollution by eliminating the need for mineral fertilizers and pesticides in agriculture (Chomo and Seggel, 2017). With increasing competition for freshwater resources, aquaponics has the potential to sustain high productivity with less labour and land while maximizing nutrient utilization and minimizing water usage (FAO, 2014; FAO, 2016a; Chomo and Seggel, 2017).

Aquaponics has other benefits too. Since it's a controlled system, it provides a level of biosecurity that reduces the risk of disease or infestation, while solving challenges found in traditional agriculture such as soil degradation, erosion, mineral fertilizer requirement, and irrigation. It's believed that aquaponics generates fewer greenhouse gas emissions to produce the same amount of product in a relatively small space by eliminating energy requirement for tilling the land or no application of mineral fertilizers (FAO, 2014; FAO, 2016a).

Large-scale commercial aquaponics requires substantial capital investment and a ready market for the often premium-priced pesticide-free vegetables and may be too expensive to small- and medium-scale farmers (Chomo and Seggel, 2017). However, for a start, FAO has prioritized supporting Small-scale Aquaponic Food Production efforts (FAO, 2014) and has invested in conducting training workshops in Eastern and Northern Africa and building demonstration sites in the Caribbean countries (FAO, 2016a; Chomo and Seggel, 2017).

Despite the high capital expenditure and technical requirement for Climate Smart Aquaculture approaches such as transgenic fish production, hyperspectral imaging for disease control, and aquaponics/hydroponics, these technologies have the potential to support economic development and enhance food security and nutrition in Africa. Unfortunately, these CSA technologies may not be easily adopted in Africa because they are not context-specific in terms of regional cultures and economies. For instance, transgenic fish may not be entrepreneurially feasible in Africa because of country-specific cultural norms and unknown long-term environmental and human health consequences (Aerni *et al.*, 2004). Additionally, expensive high-tech technologies such as hyperspectral imaging equipment for disease control may be inaccessible and unaffordable for many small- and large-scale farmers in the region. As such, contextualized technology suitable for Africa's multi-cultural situations, economic realities, and political challenges is crucial for the adoption of CSA technologies to ensure food security for the region.

*(b) Reducing vulnerability and increasing resilience to climate change impacts*

The Democratic Republic of the Congo is the second most vulnerable national economy globally to climate change-driven impacts on fisheries since its nutritionally dependent on fish (45 percent of animal protein being derived from fish) (Allison *et al.*, 2009). For such an economy, climate-smart disaster risk reduction and management strategies are valuable because climate change and climate variability can cause reduced yields from aquaculture farms arising from global warming, acidification, and pathogens (FAO, 2016a). Culture-based aquaculture (a stock enhancement process) is a smart way to improve resilience and increase fish production and diversification for food (Amarasinghe and Nguyen, 2009) using limited resources such as freshwater (De Silva 2003). Culture-based aquaculture is very relevant for species whose breeding grounds have been affected by climate change, such as (a) mussels, (b) shrimp, especially *Penaeus monodon* and freshwater prawns, (c) tuna, and (d) some high-value marine finfish (Barange *et al.,* 2018). Bivalves and seaweeds, of course, require no additional feed input.

Culture-based aquaculture is less costly, environmentally friendly and does not consume external feed resources, thus has no greenhouse gas emission related to feeding (FAO, 2016a). Financially, this would be suitable for semi-intensive to extensive aquaculture systems in Africa to ensure food security, especially in the rural communities that often share communal waterbodies. Regardless, the system is vulnerable to the unpredictability of precipitation resulting from climate change, which is beyond human control, and thus, can have a significant impact on the productivity of the system. To adapt, stocking in culture-based aquaculture can be done during the rainy season, and harvesting can take place at the onset of the dry season. Also, indigenous fish species from well-managed broodstock could be utilized to avoid genetic introgression and disease from wild stock (FAO, 2016a). Another practical option would be to introduce marine and euryhaline species (with wide salinity tolerance) or shift to coastal aquaculture-based fisheries in response to water circulation changes, water stress and drought conditions (Daw *et al.,* 2009; De Silva and Soto, 2009). Building such resilient livelihoods in Africa would equip communities with tools to withstand damage from climate change, recover quickly as well as adapt to change (IPCC, 2014). Lastly, the resilience of the aquaculture sector to climate change impacts may need adaptation efforts focused on enhancing the sustainability of aquaculture resources as well as constructing climate-resilient infrastructure such as deeper ponds, among others.

*(c) Mitigating greenhouse gas emission*

Generally, aquacultures play significant roles in reducing and/or supporting the natural removal of emissions as well as providing alternative energy sources. In aquaculture food production, feed and fertilizer and the primary and secondary contributors to greenhouse gas emissions, respectively (FAO, 2016c). It was estimated that 385 million tonnes of $CO_2$ equivalent ($CO_2$) were emitted in 2010 from the aquaculture sector, amounting to approximately 7 percent of those from agriculture (Hall *et al.,* 2011). Emissions (methane and nitrous oxide) from sediments and water systems tend to increase from the extensive system (no treatment and/or only partial fertilization) to semi-intensive (uses fertilizers and/or partial feeding) or intensive systems (fully dependent of feeds). Intensive production of finfish and crustaceans is the greatest emitter for greenhouse gases because it is heavily reliant on feeds as well as energy for water aeration (Hasan and Soto, 2017; Robb *et al.,* 2017). Comparatively, the farming of mollusks produces relatively low greenhouse gas emissions (Bonaglia *et al.,* 2017).

Additionally, energy sources (e.g. fuel) for machines and equipment (e.g. water pumps and vehicles, etc.) used in aquaculture production processes also generate greenhouse gases (FAO, 2016a; Hasan and Soto, 2017; Robb *et al.,* 2017). Energy-intensive post-harvest processing such as smoking, drying, packaging, storage, and transportation contribute to greenhouse gas emission. Newer and more efficient machines and equipment can save fuel compared to old engines. Renewable energy (e.g. wind, solar, and hydropower) could eliminate the need for diesel for hydraulics, refrigeration, heating, cooling, lighting, pumps, etc. required in aquaculture operations (Thomas, *et al.,* 2010).

Models indicate that using better technologies, renewable energy, improving feed conversion rates, and formulating fish feed with crop-based ingredients instead of marine-based ingredients would greatly reduce greenhouse gas emissions in aquaculture (Waite *et al.,* 2014). Using 2010 as the baseline year, these efforts together are projected to increase global aquaculture production by 133 percent by 2050 while reducing greenhouse gas emissions by 21 percent in $CO_2$ emission per tonne of fish produced (Waite *et al.,* 2014). It's also been reported that integrated food production systems, for example, rearing fish in rice paddies would maximize food production and energy utilization sustainably while mitigating greenhouse gas emission from rice fields (Lipper *et al.,* 2017).

Additionally, integrated mangrove-shrimp cultivation can substantially reduce blue carbon emissions (carbon sequestered, stored, and released in coastal mangroves, seagrass, and salt marshes) (McLeod *et al.,* 2011; Ahmed *et al.,* 2017). Mangroves are one of the most threatened tropical ecosystems (Donato *et al.,* 2011) yet they store carbon better than other tropical upland forests (Alongi, 2014). Destruction of mangrove forests has led to an increase in emissions of blue carbon (Alongi, 2014). It's estimated that an area covered by 50 percent mangrove forest and integrated with shrimp culture can sequester 0.86–1.04 million tons of carbon per year and reduce overall greenhouse gas emissions (Ahmed *et al.,* 2017). According to Naturland organic aquaculture standards, integrated mangrove-shrimp farming can also be certified as organic aquaculture (Naturland, 2019).

Lastly, seaweed (microalgae) aquaculture in the deep seas can act as $CO_2$ sink, and if used for biofuel (bio-ethanol and biodiesels) production, has the potential to reduce greenhouse gas emissions from fossil fuels required for energy production (Duarte *et al.,* 2017). Biofuel production is an already established enterprise; it's efficiency and yields are increasing. Seaweed aquaculture can also improve soil quality and significantly eliminate the need for synthetic fertilizers in agricultural production, and when used in animal feed, help lower methane emission from cattle (Duarte *et al.,* 2017). However, inland seaweed aquaculture, grown in conventional culture systems, face challenges such as lack of suitable areas for the practice, resource competition, high capital for infrastructure installation to cope with extreme climate change impact on off-shore environments, and ready market demand for seaweed products (Duarte *et al.,* 2017; Barange *et al.,* 2018).

In Africa, reducing greenhouse gas emissions from aquaculture systems can be achieved in ways that are cost-effective and socially efficient. Some measures with the potential to improve the physical performance of fish and reduce greenhouse gas emissions include: (a) breeding for improved feed conversion ratio (FCR) (Thoa *et al.,* 2016); (b) vaccination for streptococcosis, which is likely to improve animal welfare by reducing mortality rates as well as a decrease in antibiotic use (Liu *et al.,* 2016); and (c) adding phytase to the ration to improve nutrient utilization and bioavailability (Adeoye *et al.,* 2016).

**Table 3.** A proposed framework for context-specific climate-smart aquaculture (CSA) in Africa: reducing and removing greenhouse gases (GHG).

| Theme | Component | Climate Smart Priority Actions | Context and challenges | Potential Climate Change Impacts | Opportunities and Benefits | Outcome | References |
|---|---|---|---|---|---|---|---|
| Reducing and removing greenhouse gases (GHG) | Strongly engage in greenhouse gas mitigation processes. | New feed formulations and design.<br>• Switching from feed based on fish to feed made from crop-based ingredients, insect protein meal, and microalgae. | • The feed is the primary determining factor for greenhouse gas emission levels, followed by synthetic fertilizers.<br>• Commercial aquafeeds formulations rely heavily on relatively costly fish meal and fish oil.<br>• Over-reliance on marine ingredients can lead to overfishing, making too many vessels go after fewer and fewer fish, increasing fossil fuel use, and reduces the economic efficiency of fisheries. | • Aquafeeds increase nutrient loadings in the water bodies and pond sediments in feed-based aquaculture production systems. | • Focus research to reduce the low biodigestibility of terrestrial feedstuffs.<br>• Cluster approach to access better feed.<br>• Increase research investment on better feeds and feeding.<br>• Increase the incentive to consume and farm non-fed species.<br>• Phytase addition to the feed ration in order to increase the bioavailability of nutrients and improve FCR. | • Help reduce the environmental impact of aquaculture through low carbon development.<br>• Genetic improvement for alternative feeds.<br>• Better feed management.<br>• Fish meal/oil replacement. | Naylor *et al.*, 2000<br>De Silva and Soto, 2009<br>Afinah *et al.*, 2010<br>Boyd *et al.*, 2010<br>Boyd and Tucker, 2014<br>Waite *et al.*, 2014<br>Chatvijitkul *et al.*, 2017<br>FAO, 2017d<br>MacLeod *et al.*, 2019 |

*The need for context-specific climate-smart aquaculture (CSA) framework for Africa*

According to FAO, the goal of Climate-Smart Aquaculture (CSA) is to support food and nutrition security while considering the mitigation of greenhouse gas emission as well as adaptation to a changing climate (FAO, 2013). In Africa, aquaculture-based communities are particularly vulnerable to impacts of climate change on the natural resources required for productivity and survivability of fish and other aquatic invertebrates. As such, CSA addresses challenges regarding aquaculture infrastructure development for protecting and improving production capacities and the supply chain while minimizing their potential negative trade-offs (FAO, 2013; FAO, 2016a).

Additionally, CSA is targeted at building resilience to climate change impacts on aquaculture, thus enhancing FAO's achievement of national food security and sustainable development goals (FAO, 2013), and which will require: (a) improving natural resource utilization efficiency e.g.

aquaponics/hydroponics; (b) reducing vulnerability and increasing resilience at the local level to support aquaculture-dependent communities; and (c) reducing and removing greenhouse gases, mainly carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) (Barange *et al.,* 2018). Fish farmers in Africa could help the sector achieve this by adapting to aquaculture system that ensures increased production efficiency through improved feeding (lower feed conversion ratio), proper disease diagnosis and management, use of renewable energy, and reduction of postharvest and production losses (Daw *et al.,* 2009; De Silva and Soto, 2009; FAO, 2016a). These strategies will require institutional and human capital, the involvement of private and public sectors, as well as participation at regional and national levels, to ensure the aquaculture sector is climate-smart even as the sector tries to expand economic and trade opportunities across countries.

It would be expected that regional policymakers and other stakeholders should be able to develop and implement appropriate responses to climate change in their respective regions through inclusive dialogue with neighboring countries and proper analysis of scientific data.

The success of CSA in the African region will require that climate-smart approaches are locally relevant, economically sustainable, culturally appropriate, and environmentally friendly. Even so, adaptation to the impacts of climate change and climate variability as well as mitigation strategies to reduce or limit greenhouse gas emissions must consider the use of aquaculture practices that adhere to FAO Code of Conduct for Responsible Fisheries (FAO, 1995) and whose implementation is facilitated by the ecosystem approach to fisheries and aquaculture (EAF/EAA) (FAO, 2003; FAO, 2009; FAO 2013; Chomo and Seggel, 2017). Already, Nigeria has responded by adopting integrated aquaculture to encourage increased food production; treatment of fish wastewater to minimize pollution of surrounding water bodies; adopting the use of tarpaulin ponds during dry weather; and erecting shades over the pond to control water temperature and reduce evaporation losses (Thaddeus *et al.,* 2012). Constraint to CSA in Africa may include high adaptation costs that negatively impact production and profits; unclear trade and value-added opportunities; lack of awareness, preparedness, and appropriate skills; political interactions at national and regional levels; competitiveness of exports and world trade patterns; and local social, economic and policy measures of greenhouse gas impact.

Therefore, context-specific climate-smart aquaculture processes and actions may reduce the impacts of climate change and climate variability on aquaculture systems, improve the sector's mitigation potential, build value chain resiliency and promote sustainable production and consumption while ensuring societal and environmental sustainability.

Community-based capacity building in basic aquatic resource management will ensure underlying resilience in the face of climate variability and change. OF course, community-based adaptation strategies will improve the management of farms and the choice of farmed species by facilitating understanding, and the use of inclusive devolved approaches involving local stakeholders. Adaptation measures to climate change that could be appropriate in Africa's context may include: proper zoning, planning and site selection for aquaculture through risk analysis (Cattermoul *et al.,* 2014; FAO, 2017d); adoption of environmental monitoring systems to track weather events that can trigger disease outbreak and water movements that cause toxic algal blooms (Barange *et al.,* 2018); provision of access to affordable credit and insurance for recovery from climate-change-induced damages (Karim *et al.,* 2014; FAO, 2016d, 2017e); better management practices that improve the environmental performance, productivity and profitability of aquatic farms (Barange *et al.,* 2018); technological innovations that reduce susceptibility to climate change such as aquaponics/hydroponics (Somerville *et al.,* 2014); aquaculture diversification strategies that's compatible with local ecosystems (Harvey *et al.,* 2017); and integrated agri-aquaculture production systems to maximize resource utilization and reduce greenhouse gas emission (Crespi and Lovatelli, 2011; Shelton, 2014; Barange *et al.,* 2018). Nonetheless, to facilitate mainstreaming of CSA in Africa, efforts are needed to integrate aquaculture into climate change adaptation and food security policies at every level of governance in each country to build synergies in local institutions and ensure their incorporation into development planning.

*Proposed context-specific framework for implementing climate-smart aquaculture in Africa*

Climate change is expected to impact aquaculture and fisheries-dependent economies, fishers, and fish farmers and workers throughout the value chain in a variety of ways. Therefore, context-specific approaches to climate-smart aquaculture in Africa should address the common needs of regional relevance, accuracy, accessibility, affordability, cost-effectiveness, food security, social equity, resource use, and efficiency, human nutrition and health, proper monitoring systems and enforcement, together with direct or indirect measures of greenhouse gas emission impacts.

In Africa, each country exists within a unique geographical, environmental, institutional, and socio-economic context, which means that its aquaculture systems will have different risks and vulnerabilities. Thus, context-specific approaches to climate-smart aquaculture in the region should be planned and implemented with full consideration of this complexity and need to be participatory, adaptive, and flexible, to meet the objectives of sustainable aquaculture/fisheries management and to respond to the challenges posed by climate change and climate variability. The consequences of an inefficient, poorly planned framework are likely to exacerbate the impacts of climate change and increase risks of maladaptation (Field *et al.,* 2014). For Africa, to build, strengthen and sustain productive and resilient aquatic ecosystems, CSA must be implemented across all sectors and scales of aquaculture and fisheries, with particular attention to the needs of the poor and marginalized communities. As such, this will require climate-smart aquaculture framework that has: (a) ecosystem level and long-term focus, (b) adaptive approach and management, (c) capacity to endure complexity as well as ecological and socio-economic uncertainties, (d) an integration of multiple sectors and scales, (e) inclusive stakeholder engagement and empowerment, (f) monitoring, enforcement and review capability, and lastly, (g), ecological sustainability, economic viability, and social stability.

For example, the commercial aquaculture sector depends heavily on the application of the relatively costly aquafeeds which often rely on fish meal and fish oil in their formulation. However, synthetic feeds reportedly increase nutrient loading and carbon burial in aquaculture systems (Naylor *et al.,* 2000). Moreover, overfishing of marine species is making too many vessels chasing after fewer and fewer fish, increasing fossil fuel use, and reduces economic efficiency of fisheries and raising concerns about the resilience of aquaculture to climate change (Hsieh *et al.,* 2006).

Therefore, climate-smart aquaculture strategy must consider replacing the more costly fish meal/oil with locally-sourced cheaper alternative ingredients such as grains. Breeding initiatives can then target improving feed conversion ratio (Table 1) and by reducing the low biodigestibility of terrestrial feedstuffs Fish feed formulations and recipes should deliver comparative nutrition credentials while ensuring nutrient requirements and dietary needs of the stock are met. Switching from feed based on fish to feed made from crop-based ingredients, insect protein meal and microalgae will help reduce the environmental impact of aquaculture since fishing vessels and equipment generate carbon dioxide emissions (Table 3).

To validate that transitioning to feed formulation with no marine ingredients can reduce greenhouse gas emissions and is socially efficient, Marginal Abatement Cost Curves (MACCs) modeling, which has been widely applied in the development of mitigation policy for agriculture, can be used to analyze its cost-effectiveness and to determine the marginal benefit of reducing pollution (MacLeod *et al.,* 2015). For a given measure, optimal pollution abatement occurs where the marginal cost of abatement equals the marginal benefit (Pearce and Turner, 1990). Measures can include: (a) fish breeding programs for improved feed conversion ratio (FCR) (Gjedrem *et al.,* 2012; Omasaki *et al.,* 2017), and (b) phytase addition to the feed ration to increase the bioavailability of nutrients and improve FCR (Afinah *et al.,* 2010). This is because tilapia lacks phytase in their intestines, while phytate, an indigestible form of phosphorus, is particularly common in plant raw materials, especially soybean and rice bran, and has low bioavailability for tilapia. The biological efficiency of aquaculture will be reflected in the relatively low commodity prices resulting from the reduced cost of feeding and decreased greenhouse gas emissions intensities (Table 1 and 3). Thus, cost-effectiveness analysis (CEA) using MACC model can be used to help identify the most cost-effective efficiency improvements, thereby supporting the sustainable development of aquaculture in Africa.

Extensive adaptation to climate change will also be necessary to reduce vulnerability to future climate change to the African countries. Adaptation approaches must consider the effective use of water resources and where appropriate can include climate-smart approaches such as aquaponics (Table 1), integrated production systems to increase food diversification (Table 2) and improved pond design (Table 2).

(a) While some aquaculture innovations and practices have focused on ensuring a high-quality and consistent supply of farmed fish to the markets (Kumar *et al.,* 2016), several factors influence aquaculture technology adoption by communities (Dey *et al.,* 2010; Wetengere, 2011; Kumar *et al.,* 2018). Unfortunately, little is known about the scale of impacts of technological change in African agriculture in general (Glover *et al.,* 2016), especially in socio-economically vulnerable human societies such as those found in rural communities. However, since many donors are advocating for the mainstreaming of climate change adaptation and resilience in policies on food systems and value chains in developing countries (Ayers *et al.,* 2014; Sherman *et al.,* 2016), we believe implementing climate-smart aquaculture in context-specific environments in Africa as a means of addressing climate change and community-based disaster risk management would have the following considerations. Understanding of gaps in system resilience, greenhouse emission and productivity potential.

(b) Protection of natural resources as well as the efficiency of resource use.

(c) Improvement of rural livelihoods and incomes.

(d) Nutritional security.

(e) Personal and community empowerment.

(f) Vulnerability reduction.

(g) Understanding of widespread social marginalization and poverty in fishing communities.

(h) Climate change and the potential risks to productivity, stocks, and human health.

(i) Mechanisms for community-based responses.

(j) Ecosystem complexity, communities, and governance structures.

(k) An integrated and participatory approach to managing fisheries and aquaculture systems.

(l) Cultural factors such as community norms.

(m) Limited availability of inputs in local markets.

(n) Absence of credit, microfinance, insurance, and other support measures.

(o) Ancillary effects on the environment, animal welfare, or human health.

(p) Post-harvest practices at the farm-level.

(q) Concept of sustainable intensification and country-specific biophysical, socio-economic dynamics, institutional and market capacity, regional geopolitics, and varying local needs and interests.

(r) Emerging technologies including renewable energy sources.

Finally, we believe that adopting and transitioning to

CSA in Africa will be based on the potential impact of the proposed climate smart priority areas, sector-specific relevance, farm-specific characteristics, and size, production status, diversification of other agricultural activities, resource accessibility, extension services availability, cost-effectiveness, individual country's adaptive capacity, governance structure, and aquatic resource management policies. Of course, economic and market-based incentives would make the CSA self-sustaining. However, institutional change and strengthening, public and private sector investment, and the development of proper infrastructure and participatory monitoring systems will be required. One approach would be to develop national climate change policies and aquaculture programs integrated with broader development objectives such as food security, sustainability, social equity, and biodiversity, with partnership and support from regional agencies, stakeholders, development partners, governments, and administrations.

**Conclusion**

Fish is the most accessible and affordable source of animal protein, especially for the 'poor' socioeconomic classes in Africa, and demand and consumption of fish products will continue to increase due to increasing income levels and awareness of nutritional and health benefits of fish. However, the growth of fish production in Africa is not immune to climate-induced problems as competition for land, water, energy, and feed resources intensifies. The contributions of the aquaculture sector to global emissions of greenhouse gases are discussed and we have provided context-specific methods for reducing greenhouse gas emissions, including (a) improving feed conversion rates, and (b) switching from feed based on fish to feed made from crop-based ingredients, insect protein meal, and microalgae. We have proposed a framework leveraging the principles described in FAO's ecosystem approach to fisheries and aquaculture (EAF/EAA) strategies and then modified for context-specific environments in Africa while considering the FAO Code of Conduct for Responsible Fisheries to maximize success. The proposed framework is structured for the African context and economies and has climate-smart strategies for (a) sustainable intensification, (b) vulnerability reduction and resilience building, and lastly, (c) greenhouse gas mitigation. Based on the empirical literature, prioritizing these actions in the African context will depend on the prevailing geopolitics, laws and regulations, socio-economic statuses, specific community needs, market capacity, trade/tariff laws, unique institutional factors, exposure, sensitivity, and the nature of vulnerability within every country and region.

*Disclosure statement*

All authors declare that they have no conflict of interest.

*Funding*

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**References**

**Adeoye AA, Jaramillo-Torres A, Fox SW, Merrifield DL, Davies SJ.** 2016. Supplementation of formulated diets for tilapia (*Oreochromis niloticus*) with selected exogenous enzymes: Overall performance and effects on intestinal histology and microbiota. Animal Feed Science and Technology **215,** 133–143. https://doi.org/10.1016/j.anifeedsci.2016.03.002

**Aerni P.** 2004. Risk, regulation and innovation: The case of aquaculture and transgenic fish. Aquatic Sciences **66,** 327-341. https://doi.org/10.1007/s00027-004-0715-8

**Afinah S, Yazid AM, Anis Shobirin MH, Shuhaimi, M.** 2010. Phytase: application in food industry. International Food Research Journal **17,** 13–21.

**Ahmed N, Thompson S, Glaser M.** 2017. Integrated mangrove-shrimp cultivation: potential for blue carbon sequestration. Ambio **47**, 441-452. https://doi.org/10.1007/s13280-017-0946-2.

**Ahn JH, Kim S, Park H, Rahm B, Pagilla K, Chandran K.** 2010. N2O emissions from activated sludge processes, 2008– 2009: results of a national monitoring survey in the United States. Environmental Science and Technology **44,** 4505-11. https://doi.org/10.1021/es903845y

**Akrofi J.** 2002. 24 Fish utilisation and marketing in Ghana: State of the art and future perspective. Large Marine Ecosystems **11,** 345-354. https://doi.org/10.1016/S1570-0461(02)80046-5

**Allison EH, Adger WN, Badjeck MC, Brown K, Conway D, Dulvy NK, Halls A, Perry A, Reynolds JD.** 2005. Effects of climate change on the sustainability of capture and enhancement fisheries important to the poor: analysis of the vulnerability and adaptability of fisherfolk living in poverty. Final Technical Report. https://agris.fao.org/agris-search/search.do?recordID=GB2012105545

**Allison EH, Andrew NL, Oliver J.** 2007. Enhancing the resilience of inland fisheries and aquaculture systems to climate change. The Journal of Semi-Arid Tropical Agricultural Research **4,** 1-35.

**Allison EH, Perry AL, Badjeck MC, Neil Adger W, Brown K, Conway D, Halls AS, Pilling GM, Reynolds JD, Andrew NL, Dulvy NK.** 2009. Vulnerability of national economies to the impacts of climate change on fisheries. Fish and fisheries **10,** 173-96. https://doi.org/10.1111/j.1467-2979.2008.00310.x

**Alltech.** 2014. Global Feed Survey Summary. http://www.animalfeedmarket.com/wpcontent/uploads/2017/03/Alltech-global-feedsummary-2014.

**Alongi DM.** 2014. Carbon cycling and storage in mangrove forests. Annual Review of Marine Science **6,** 195–219. https://doi.org/10.1146/annurevmarine-010213-135020.

**Amankwah A, Quagrainie KK, Preckel PV.** 2016. Demand for improved fish feed in the presence of a subsidy: a double hurdle application in Kenya. Agricultural Economics **47,** 633–643. https://doi.org/10.1111/agec.12261

**Amankwah A, Quagrainie KK, Preckel PV.** 2018. Impact of aquaculture feed technology on fish income and poverty in Kenya. Aquaculture Economics and Management **22,** 410-430. https://doi.org/10.1080/13657305.2017.1413689

**Amarasinghe US, Nguyen, TTT.** 2009. Enhancing rural farmer income through fish production: secondary use of water resources in Sri Lanka and elsewhere. In De Silva SS and Davy FB, eds. Success stories in Asian aquaculture, p 115-133. https://doi.org/10.1007/978-90-481-3087-0_6

**Anderson DM.** 2009. Approaches to monitoring, control and management of harmful algal blooms (HABs). Ocean and Coastal Management **52,** 342–347. https://doi.org/10.1016/j.ocecoaman.2009.04.006).

**Anderson JL, Asche F, Garlock T, Chu J.** 2017. Aquaculture: Its role in the future of food. In Frontiers of Economics and Globalization; Emerald Publishing Limited: Bradford, UK **17,** p 159–173. https://doi.org/10.1108/S1574-871520170000017011

**Aswani S, Howard JAE, Gasalla MA, Jennings S, Malherbe W, Martins IM, Salim SS, Van Putten IE, Swathilekshmi PS, Narayanakumar R, Watmough GR.** 2018. An integrated framework for assessing coastal community vulnerability across cultures, oceans and scales. Climate and Development **11,** 365-82. https://doi.org/10.1080/17565529.2018.1442795.

**AUC-NEPAD.** 2014a. African Union Commission New Partnership for Africa's Development (AUC-

NEPAD). Malabo Declaration on Accelerated Agricultural Growth and Transformation for Shared Prosperity and Improved Livelihoods. 2003. https://www.nepad.org/caadp/publication/malabo-declaration-acceleratedagricultural-growth

**AUC-NEPAD.** 2014b. The Policy Framework and Reform Strategy for Fisheries and Aquaculture in Africa; NEPAD: Johannesburg, South Africa, 2014. https://wedocs.unep.org/bitstream/handle/20.500.11822/26707/ReformStrategyFisheries.pdf

**Ayers JM, Huq S, Faisal AM, Hussain ST.** 2014. Mainstreaming climate change adaptation into development: a case study of Bangladesh. Wiley Interdisciplinary Reviews: Climate Change **5**, 37-51. https://doi.org/10.1002/wcc.226

**Asiedu B, Failler P, Beyens Y.** 2016. Enhancing aquaculture development: mapping the tilapia aquaculture value chain in Ghana. Reviews in Aquaculture **8,** 394-402. https://doi.org/10.1111/raq.12103

**Satia BP.** 2011. Regional Review on Status and Trends in Aquaculture Development in Sub-saharan Africa-2010. FAO Fisheries and Aquaculture Circular. 2011(C1061/4). https://search.proquest.com/openview/5dc5e4dd60c8f5057012725bbe3042b1/1?pq-origsite=gscholar&cbl=237324

**Barange M, Perry I.** 2009. Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In: Cochrane K, De Young C, Soto D, Bahi T. (eds). Climate change implications for fisheries and aquaculture: Overview of current scientific knowledge. Fisheries Technical Paper, 530. FAO, Rome, p 07-95. http://www.ipcinfo.org/fileadmin/user_upload/newsroom/docs/FTP530.pdf#page=13

**Barange M, Bahri T, Beveridge MC, Cochrane KL, Funge-Smith S, Poulain F.** 2018. Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. United Nations' Food and Agriculture Organization. Technical Paper No. 627. Rome, FAO, p. 628.

**Barange M, Merino G, Blanchard JL, Scholtens J, Harle J, Allison EH, Allen JI, Holt J, Jennings S.** 2014. Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nature Climate Change **4,** 211-6. https://doi.org/10.1038/nclimate2119

**Béné C, Barange M, Subasinghe R, Pinstrup-Andersen P, Merino G, Hemre GI, Williams M.** 2015.Feeding 9 billion by 2050–Putting fish back on the menu. Food Security **7,** 261-74. https://doi.org/10.1007/s12571-015-0427-z

**Béné C, Heck S.** 2005. Fish and food security in Africa. NAGA, WorldFish Center Quarterly **28,** 8-13.

**Beveridge MC, Thilsted SH, Phillips MJ, Metian M, Troell M, Hall SJ.** 2013. Meeting the food and nutrition needs of the poor: the role of fish and the opportunities and challenges emerging from the rise of aquaculturea. Journal of fish biology **83,** 1067-84. https://doi.org/10.1111/jfb.12187

**Boko M, Niang I, Nyong A, Vogel C, Githeko A, Medany M, Osman-Elasha B, Tabo R, Yanda P.** 2007. Africa: Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, (Eds.), Cambridge University Press, Cambridge UK, p. 433-467.

**Bonaglia S, Brüchert V, Callac N, Vicenzi A, Chi Fru E, Nascimento FJA**. 2017. Methane fluxes from coastal sediments are enhanced by macrofauna. Scientific Reports. https://doi.org/10.1038/s41598-017-13263-w

**Bostock J, Seixas S.** 2015. Investing in the human capital of the aquatic food sector: AQUA-TNET and the road ahead. Aquaculture International **23**, 861 881.
https://doi.org/10.1007/s10499-015-9915-6

**Boyd CE, Tucker CS.** 2014. Handbook for Aquaculture Water Quality (Craftmaster Printers, Auburn, p 439.
https://www.ars.usda.gov/research/publications/publication/?seqNo115=303721

**Boyd CE, Wood CW, Chaney PL, Queiroz JF.** 2010. Role of aquaculture pond sediments in sequestration of annual global carbon emissions. Environmental pollution **158,** 2537-40.
https://doi.org/10.1016/j.envpol.2010.04.025

**Brander K.** 2010. Impacts of climate change on fisheries. Journal of Marine Systems **79,** 389-402.
https://doi.org/10.1016/j.jmarsys.2008.12.015

**Brummett RE, Lazard J, Moehl J.** 2008. African aquaculture: realizing the potential. Food Policy **33,** 371385.
https://doi.org/10.1016/j.foodpol.2008.01.005

**Cai J, Huang H, Leung PS.** 2019. Understanding the Contribution of Aquaculture and Fisheries to GDP; FAO Fisheries and Aquaculture Technical Paper No. 606; FAO: Rome, Italy, p 80

**Cai J, Leung PS.** 2017. Short-Term Projection of Global Fish Demand and Supply Gaps; FAO Fisheries and Aquaculture Technical Paper No. 607; FAO: Rome.

**Cattermoul B, Brown D, Poulain F.** 2014. Fisheries and aquaculture emergency response guidance. Rome, FAO, p 167.
http://www.fao.org/3/a-i3432e.

**Chan CY, Tran N, Pethiyagoda S, Crissman CC, Sulser TB, Phillips MJ.** 2019. Prospects and challenges of fish for food security in Africa. Global Food Security **20,** 17–25.
https://doi.org/10.1016/j.gfs.2018.12.002

**Chatvijitkul S, Boyd CE, Davis DA, McNevin AA.** 2017. Pollution potential indicators for feed-based fish and shrimp culture. Aquaculture **477,** 43–49.
https://doi.org/10.1016/j.aquaculture.2017.04.034

**Cheung WW, Lam VW, Sarmiento JL, Kearney K, Watson RE, Zeller D, Pauly D.** 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology **16,** 24-35.
https://doi.org/10.1111/j.1365-2486.2009.01995.x

**Chomo V, Seggel A.** 2017. Climate-Smart fisheries and aquaculture in FAO Climate Smart Agriculture Sourcebook. Update of Module 10 Climate-smart fisheries and aquaculture in the Climate-Smart Agriculture Sourcebook.
http://www.fao.org/climate-smart-agriculture-sourcebook/production-resources/module-b4-fisheries/b4-overview/en/

**Cochrane K, De Young C, Soto D, Bahri T.** 2009. Climate change implications for fisheries and aquaculture. FAO Fisheries and aquaculture technical paper No. 530, p 530:212.
http://www.ipcinfo.org/fileadmin/user_upload/newsroom/docs/FTP530.pdf

**Crespi V, Lovatelli A.** 2011. Aquaculture in desert and arid lands: development constraints and opportunities. FAO Technical Workshop, 6–9 July 2010, Hermosillo, Mexico. FAO Fisheries and Aquaculture Proceedings No. 20. Rome, FAO, p 202.
http://www.fao.org/docrep/015/ba0114e/ba0114e.pdf).

**Tweddle D, Cowx IG, Peel RA, Weyl OL.** 2015. Challenges in fisheries management in the Zambezi, one of the great rivers of Africa. Fisheries Management and Ecology **22,** 99-111.
https://doi.org/10.1111/fme.12107

**Darko FA, Quagrainie KK, Chenyambuga S.** 2016. Consumer preferences for farmed tilapia in Tanzania: A choice experiment analysis. Journal of Applied Aquaculture **28,** 131-43.
https://doi.org/10.1080/10454438.2016.1169965

**Daw T, Adger N, Brown K, Badjeck MC.** 2008. 'Climate change and capture fisheries: potential impacts, adaptation and mitigation' in Cochrane K, Young CD, Soto D. and Bahri, T.(eds) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge.
https://ueaeprints.uea.ac.uk/id/eprint/29707/1/FAO-2009-CCimplications-for-fisheries.pdf

**De Graaf GJ, Garibaldi L.** 2014.The Value of African Fisheries; Vol FIPS/C1093, FAO: Rome, Italy, p 67.
http://www.fao.org/documents/card/es/c/d155e4db-78eb-4228-8c8c-7aae5fc5cb8e/

**De San M.** 2013. Report of Five EAC's Countries Aquaculture Situation, Needs and Regional Expectations; Report/Rapport: FAO SmartFish Publication No. SF-FAO/2013/12; FAO: Arusha, Tanzania.
http://www.fao.org/3/a-az018e.pdf

**De Silva SS.** 2003. Culture-based fisheries: an underutilised opportunity in aquaculture development. Aquaculture **221,** 221-243.
https://doi.org/10.1016/S0044-8486(02)00657-9

**De Silva SS, Soto D.** 2009. Climate change and aquaculture: potential impacts, adaptation and mitigation. In Cochrane K, De Young C, Soto D, Bahri T (eds). Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. Rome, FAO, p 151-212.
http://www.fao.org/fileadmin/user_upload/newsroom/docs/FTP530.pdf#page=157

**Dey MM, Paraguas FJ, Kambewa P, Pemsl DE.** 2010. The impact of integrated aquaculture-agriculture on smallscale farms in Southern Malawi. Agricultural Economics **41,** 67–79.
https://doi.org/10.1111/j.1574-0862.2009.00426.x

**Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M.** 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience **4**, 293–297.
https://doi.org/10.1038/ngeo1123

**Duarte CM, Wu J, Xiao X, Bruhn A, Krause-Jensen D.** 2017. Can seaweed farming play a role in climate change mitigation and adaptation? Frontiers in Marine Science **4,** 100.
https://doi.org/10.3389/fmars.2017.00100

**Elsaidy N, Abouelenien F, Kirrella GA.** 2015. Impact of using raw or fermented manure as fish feed on microbial quality of water and fish. The Egyptian Journal of Aquatic Research **41,** 93-100.
https://doi.org/10.1016/j.ejar.2015.01.002

**Engle CR.** 2017. The case for effective public funding of aquaculture research and extension. Journal of the World Aquaculture Society **48,** 851–853.
https://doi.org/10.1111/jwas.12487

**Fairweather TP, van der Lingen CD, Booth AJ, Drapeau L, van der Westhuizen JJ**. 2006. Indicators of sustainable fishing for South African sardine Sardinops sagax and anchovy Engraulis encrasicolus. African Journal of Marine Science **28,** 661–680.
https://doi.org/10.2989/18142320609504215

**FAO.** 1995. Code of conduct for responsible fisheries. Rome, FAO, p 41.
http://www.fao.org/docrep/005/v9878e/v9878e00.htm

**FAO.** 2003. The ecosystem approach to fisheries. FAO Technical Guidelines for Responsible Fisheries.No. 4, Suppl. 2. Rome, FAO, p 112.
ftp://ftp.fao.org/docrep/fao/005/y4470e/y4470e00.pdf

**FAO**. 2009. Fisheries management. 2. The ecosystem approach to fisheries. 2.2 Human dimensions of the ecosystem approach to fisheries. FAO Technical Guidelines for Responsible Fisheries. No. **4(2),** Add. 2. Rome, FAO, p 88. http://www.fao.org/docrep/012/i1146e/i1146e00.pdf

**FAO.** 2010a. Climate change implications for food security and natural resources management in Africa, Luanda, Angola, 03-07-May 2010. Rome: FAO.

**FAO.** 2010b. Aquaculture development. 4. Ecosystem approach to aquaculture. FAO Technical Guidelines for Responsible Fisheries No. **5(4),** Rome, p 53. http://www.fao.org/docrep/013/i1750e/i1750e.pdf

**FAO.** 2012. Voluntary guidelines on the responsible governance of tenure of land, fisheries and forestry in the context of national food security. Rome, p 40. http://www.fao.org/docrep/016/i2801e/i2801e.pdf

**FAO.** 2013. Climate-smart agriculture. Sourcebook. Rome, p 241 – 271. http://www.fao.org/3/a-i3325e.pdf

**FAO.** 2014. Small scale aquaponic food production. Integrated fish and plant farming. Rome.

**FAO.** 2015. Voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication. Rome, p. 18. http://www.fao.org/3/i4356en/I4356EN.pdf

**FAO.** 2016a. The State of World Fisheries and Aquaculture 2016. Rome.

**FAO.** 2016b. Climate change implications for fisheries and aquaculture: Summary of the findings of the Intergovernmental Panel on Climate Change Fifth Assessment Report. FAO Fisheries and Aquaculture Circular No. C1122. Rome.

**FAO.** 2016c. Reducing Feed Conversion Ratios in Global Aquaculture to Reduce Carbon and Other Footprints and Increase Efficiency. Proceedings of the FAO/Global Salmon Initiative Joint Workshop on 9 – 11 November 2015, Liberia, Costa Rica.

**FAO.** 2016d. Aquaculture insurance in Viet Nam: experiences from the pilot programme, by K.A.T. Nguyen and T. Pongthanapanich. FAO Fisheries and Aquaculture Circular No. 1133. Rome, P 20. http://www.fao.org/3/a-i6559e.pdf

**FAO.** 2016e. Scoping study on decent work and employment in fisheries and aquaculture: Issues and actions for discussion and programming. Rome, p. 95. http://www.fao.org/3/a-i5980e.pdf

**FAO.** 2017a. FAO, FAOSTAT statistics database. Food balance sheets, 2017. http://www.fao.org/faostat/en/#data/FBS

**FAO.** 2017b. Food and Agriculture Organization of the United Nations (FAO). FAO Working for SDG 14: The Special Role of Fish in Human Nutrition; FAO: Rome, Italy, 2017. http://www.fao.org/3/a-i7298e.pdf

**FAO.** 2017c. Food and Agriculture Organization of the United Nations (FAO). Regional Review on Status an Trends in Aquaculture Development in Sub-Saharan Africa—2015; Satia, B., Ed.; Fisheries and Aquaculture Circular No. 1135/2; FAO: Rome, Italy, 2017; 4.

**FAO.** 2017d. Adaptation strategies of the aquaculture sector to the impacts of climate change, by P.B. Bueno & D. Soto. FAO Fisheries and Aquaculture Circular No. 1142. Rome, p 28. http://www.fao.org/3/a-i6943e.pdf

**FAO.** 2017e. Fishery and aquaculture insurance in China, by Y. Xinhua, T. Pongthanapanich, Z. Zongli, J. Xiaojun & M. Junchao. FAO Fisheries and Aquaculture Circular No. 1139, Rome, p 30. http://www.fao.org/3/a-i7436e.pdf

**FAO.** 2018a. Food and Agriculture Organization of the United Nations (FAO). World Aquaculture

Performance Indicators (WAPI)—Aquaculture Production Module (WAPI-AQPRN v.2018.1); FAO: Rome, Italy, 2018. www.fao.org/fishery/statistics/software/wapi/enpdf

**FAO.** 2018b. Food and Agriculture Organization of the United Nations (FAO). The State of World Fisheries and Aquaculture 2018—Meeting the Sustainable Development Goals; FAO: Rome, Italy

**FAO.** 2018c. Food and Agriculture Organization of the United Nations (FAO). World Food and Agriculture-Statistical Pocketbook 2018; Rome: Licence: CC BY-NC-SA 3.0 IGO; FAO: Rome, Italy, 2018. https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/WESP2019_BOOKweb.pdf

**FAO.** 2018d. FAO; IFAD; UNICEF; WFP WHO. The State of Food Security and Nutrition in the World 2018. Building Climate Resilience for Food Security and Nutrition; FAO: Rome, Italy, 2018. http://www.fao.org/3/I9553EN/i9553en.pdf

**FAO and World Bank.** 2015. Aquaculture zoning, site selection and area management under the ecosystem approach to aquaculture. Policy brief. Rome. https://www.cabdirect.org/cabdirect/abstract/20183279398

**Ficke AD, Myrick CA, Hansen LJ.** 2007. Potential impacts of global climate change on freshwater fisheries. Reviews in Fish Biology and Fisheries **17,** 581-613. https://doi.org/10.1007/s11160-007-9059-5

**Field CB, Barros VR, Dokken DJ, Mach KJ.** 2014. Climate Change 2014: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415379

**Genschick S, Kaminski AM, Kefi AS, Cole SM.** 2017. Aquaculture in Zambia: An Overview and Evaluation of the Sector's Responsiveness to the Needs of the Poor. CGIAR Research Program on Fish Agri-Food Systems and Lusaka, Zambia: Department of Fisheries, Penang, Malaysia. http://pubs.iclarm.net/resource_centre/FISH-2017-08.pdf

**Githukia CM, Obiero KO, Manyala JO, Ngugi CC, Quagrainie KK.** 2014. Consumer perceptions and preferences of wild and farmed Nile Tilapia (*Oreochromis niloticus* ) and African Catfish (*Clarias gariepinus*) in urban centres in Kenya. International Journal of Advanced ResearchInt **7,** 694–705.

**Gjedrem T, Robinson N, Rye M.** 2012. The importance of selective breeding in aquaculture to meet future demands for animal protein: a review. Aquaculture **350**, 117-29. https://doi.org/10.1016/j.aquaculture.2012.04.008

**Glover D, Sumberg J, Andersson JA.** 2016. The adoption problem; or why we still understand so little about technological change in African agriculture. Outlook Agriculture **45,** 3–6. https://doi.org/10.5367/oa.2016.0235

**Golden CD, Allison EH, Cheung WW, Dey MM, Halpern BS, McCauley DJ, Smith M, Vaitla B, Zeller D, Myers SS.** 2016. Nutrition: Fall in fish catch threatens human health. Nature News **16,** 317-320. https://doi.org/10.1038/534317a

**Golden CD, Seto KL, Dey MM, Chen OL.** 2017. Does aquaculture support the needs of nutritionally vulnerable nations? Frontiers in Marine Science **4,** 1–7. https://doi.org/10.3389/fmars.2017.00159

**Green BW.** 2015. Feed and Feeding Practices in Aquaculture (ed. Davis, D. A.) Woodhead Publishing, Cambridge, p 27-52.

**Hall SJ, Delaporte A, Phillips MJ, Beveridge MCM, O'Keefe M.** 2011. Blue frontiers: managing the environmental costs of aquaculture. Penang, Malaysia, WorldFish Centre, p 93. http://pubs.iclarm.net/resource_centre/WF_2818.pdf

**Handisyde N, Telfer TC, Ross LG.** 2017. Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. Fish and Fisheries **18,** 466–488. https://doi.org/10.1111/faf.12186

**Handisyde NT, Ross LG, Badjeck MC, Allison EH.** 2006. The effects of climat change on world aquaculture: a global perspective. Final Technical Report, DFID Aquaculture and Fish Genetics Research Programme, Stirling Institute of Aquaculture, Stirling, U.K, p 151. www.aqua.stir.ac.uk/GISAP/pdfs/Climate_full.pdf

**Harvey B, Soto D, Carolsfeld J, Beveridge M, Bartley DM.** 2017. Planning for aquaculture diversification: the importance of climate change and other drivers. FAO Technical Workshop, 23–25 June 2016, FAO Rome. FAO Fisheries and Aquaculture Proceedings No. 47. Rome, FAO, p 166.

**Hasan MR, Soto D.** 2017. Improving feed conversion ratio and its impact on reducing greenhouse gas emissions in aquaculture. FAO Non-Serial Publication. Rome, FAO, p 33. http://www.fao.org/3/a-i7688e.pdf

**Henriksson PJG, Zhang W, Nahid SAA, Newton R, Phan LT, Dao HM, Zhang Z, Jaithiang J, Andong R, Chaimanuskul K, Vo NS, Hua HV, Haque MM, Das R, Kruijssen F, Satapornvanit K, Nguyen PT, Liu Q, Liu L, Wahab MA, Murray FJ, Little DC, Guinée JB.** 2014. Final LCA case study report. Primary data and literature sources adopted in the SEAT LCA studies. SEAT Deliverable Ref: D 3.5. Annex report. Stirling, United Kingdom, SEAT Project, p 121. http://media.leidenuniv.nl/legacy/d35annexreport.pdf

**Hsieh CH, Reiss CS, Hunter JR, Beddington JR, May RM, Sugihara G.** 2006. Fishing elevates variability in the abundance of exploited species. Nature **443,** 859-62. https://doi.org/10.1038/nature05232

**Hu Z, Lee JW, Chandran K, Kim S, Sharma K, Khanal SK.** 2014. Influence of carbohydrate addition on nitrogen transformations and greenhouse gas emissions of intensive aquaculture system. Science of the total environment **1**, 193-200. https://doi.org/10.1016/j.scitotenv.2013.09.050

**Hu Z, Lee JW, Chandran K, Kim S, Khanal SK.** 2012. Nitrous oxide (N2O) emission from aquaculture: a review. Environmental science and technology **46**, 6470-80. https://doi.org/10.1021/es300110x

**IPCC.** 2007. The Fourth Assessment Report from the Intergovernmental Panel on Climate Change (IPPC). Geneva, Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

**IPCC.** 2014. The Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPPC): Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, eds. Cambridge, UK and NY, Cambridge University Press.

**Jiménez Cisneros BE, Oki T, Arnell NW, Benito G, Cogley JG, Döll P, Jiang T, Mwakalila SS.** 2014. Freshwater resources. In Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, eds. Climate change 2014: Impacts, adaptation, and vulnerability. Part B:

Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, Cambridge University Press, p 229–2690. https://www.ipcc.ch/pdf/assessmentreport/ar5/wg2/WGIIAR5-Chap3_FINAL.pdf

**Joffre OM, Klerkx L, Dickson M, Verdegem M.** 2017. How is innovation in aquaculture conceptualized and managed? A systematic literature review and reflection framework to inform analysis and action. Aquaculture **470,** 129–148. https://doi.org/10.1016/j.aquaculture.2016.12.020

**Kaminski AM, Genschick S, Kefi AS, Kruijssen F.** 2017 Commercialization and upgrading in the aquaculture value chain in Zambia. Aquaculture **493,** 355–364. https://doi.org/10.1016/j.aquaculture.2017.12.010

**Kareko J, Muriuki F, Kanyange N.** 2011. Livelihood Sustainability through Raising Community Capacity for Fisheries/Coastal Management (RaCCCoM) in Lamu Archipelago, Lamu District, Kenya: Final Evaluation Report. www.norad.no/en/toolsandpublications/publications/reviews-fromorganisations/publication?key=393425

**Karim M, Castine S, Brooks A, Beare D, Beveridge M, Phillips M.** 2014. Asset or liability? Aquaculture in a natural disaster prone area. Ocean and Coastal Management **96,** 188–197. https://doi.org/10.1016/j.ocecoaman.2014.04.021.

**Katikiro RE, Macusi ED.** 2012. Impacts of climate change on West African fisheries and its implications on food production. Journal of Environmental Science and management **15,** 83-95.

**KNBS.** 2018. Kenya National Bureau of Statistics (KNBS). Economic Survey 2018; Kenya National Bureau of Statistics (KNBS): Nairobi, Kenya.

**Kris-Etherton PM, Harris WS, Appel LJ.** 2002. Fish consumption, fish oil, omega-3 fatty acids, and cardiovascular disease. Circulation **106,** 2747–2757. https://doi.org/10.1161/01.CIR.0000038493.65177.94

**Kruijssen F, McDougal CL, Van Asseldonk IJM.** 2018. Gender and aquaculture value chains: a review of key issues and implications for research. Aquaculture **493,** 328–337. https://doi.org/10.1016/j.aquaculture.2017.12.038

**Kuehne G, Llewellyn R, Pannell DJ, Wilkinson R, Dolling P, Ouzman J, Ewing M.** 2017. Predicting farmer uptake of new agricultural practices: a tool for research, extension and policy. Agricultural systems **156,** 115–125. https://doi.org/10.1016/j.agsy.2017.06.007

**Kumar G, Engle C, Tucker C.** 2018. Factors driving aquaculture technology adoption. Journal of the World Aquaculture Society **49,** 447–476. https://doi.org/10.1111/jwas.12514

**Kumar G, Engle CR.** 2016. Technological advances that led to growth of shrimp, salmon, and tilapia farming. Reviews in Fisheries Science and Aquaculture **24,** 136–152. https://doi.org/10.1080/23308249.2015.1112357

**Kassam L, Dorward A.** 2017. A comparative assessment of the poverty impacts of pond and cage aquaculture in Ghana. Aquaculture **470,** 110-122. https://doi.org/10.1016/j.aquaculture.2016.12.017

**Lipper L, McCarthy N, Zilberman D, Asfaw S, Branca G. eds.** 2017. Climate smart agriculture: building resilience to climate change. Springer International, p 630

**Little DC, Newton RW, Beveridge MC.** 2016. Aquaculture: a rapidly growing and significant source of sustainable food? Status, transitions and potential. Proceedings of the Nutrition Society **75,** 274-86. https://doi.org/10.1017/S0029665116000665

**Liu G, Zhu J, Chen K, Gao T, Yao H, Liu Y, Zhang W, Lu C.** 2016. Development of Streptococcus agalactiae vaccines for tilapia. Diseases of aquatic organisms **122,** 163-70. https://doi.org/10.3354/dao03084

**Kobayashi M, Msangi S, Batka M, Vannuccini S, Dey MM, Anderson JL.** 2015. Fish to 2030: the role and opportunity for aquaculture. Aquaculture economics and management **19,** 282-300. https://doi.org/10.1080/13657305.2015.994240

**MacLeod M, Eory V, Gruere G, Lankoski J.** 2015. Cost-Effectiveness of Greenhouse gas mitigation measures for agriculture: A literature review. OECD Food, Agriculture and Fisheries Papers, No. 89. Paris, OECD Publishing, p 73.

**MacLeod M, Hasan MR, Robb DHF, Mamun-Ur-Rashid M.** 2019. Quantifying and mitigating greenhouse gas emissions from global aquaculture. FAO Fisheries and Aquaculture Technical Paper No. 626. Rome, FAO.

**Martins CI, Eding EH, Verdegem MC, Heinsbroek LT, Schneider O, Blancheton JP, d'Orbcastel ER, Verreth JA.** 2010. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. Aquacultural engineering **43,** 83-93. https://doi.org/10.1016/j.aquaeng.2010.09.002

**Mcleod E, Chmura GL, Bouillon S, Salm R, Björk M, Duarte CM, Lovelock CE, Schlesinger WH, Silliman BR.** 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment **9,** 552-60. https://doi.org/10.1890/110004

**Meijer SS, Catacutan D, Ajayi OC, Sileshi GW.** 2015. The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub- Saharan Africa. International Journal of Agricultural sustainability **13,** 40–54. https://doi.org/10.1080/14735903.2014.912493

**Morgan M, Choudhury A, Braun M, Beare D, Benedict J, Kantor P.** 2015. Understanding the gender dimensions of adopting climate-smart smallholder aquaculture innovations. Penang, Malaysia: CGIAR Research Program on Aquatic Agricultural Systems. Working Paper: AAS-2015-08. http://pubs.iclarm.net/resource_centre/AAS-2015-08.pdf.

**Mwima H, Monor VG, Mbilinyi HG, Rathacharen S, Omanyi PB, Katonda IK.** 2012. Regional Assessment of Fisheries Issues, Challenges and Opportunities for Eastern Africa Region; African Union. Interafrican Bureau for Animal Resources, Nairobi, Kenya: Nairobi, Kenya. http://www.au-ibar.org/general-publications

**Naylor RL, Goldburg RJ, Primavera JH, Kautsky N, Beveridge MC, Clay J, Folke C, Lubchenco J, Mooney H, Troell M.** 2000. Effect of aquaculture on world fish supplies. Nature **405,** 1017-24. https://doi.org/10.1038/35016500

**Ndah HT.** 2015. Adoption and adaptation of innovations - assessing the diffusion of selected agricultural innovations in Africa. PhD Dissertation, Humboldt-University of Berlin. https://doi.org/10.13140/2.1.2452.9285

**Obiero K, Meulenbroek P, Drexler S, Dagne A, Akoll P, Odong R, Kaunda-Arara B, Waidbacher H.** 2019a. The contribution of fish to food and nutrition security in Eastern Africa: emerging trends and future outlooks. Sustainability **11,** 1636. https://doi.org/10.3390/su11061636

**Obiero KO, Waidbacher H, Nyawanda BO, Munguti JM, Manyala JO, Kaunda-Arara B.** 2019b Predicting uptake of aquaculture technologies among smallholder fish farmers in Kenya.

Aquaculture International **27**, 1689-707.
https://doi.org/10.1007/s10499-019-00423-0

**Obiero K, Cai J, Abila R, Ajayi O.** 2019c. Kenya: high aquaculture growth needed to improve food security and nutrition, Rome, Italy.
http://www.fao.org/3/ca4693en/ca4693en.pdf

**OECD.** 2018. Organisation for Economic Co-operation and Development (OECD); Food and Agriculture Organization of the United Nations (FAO). Chapter 8. Fish and seafood. In OECD/FAO Agricultural Outlook 2018–2027; FAO: Rome, Italy, p 175–190.
http://www.fao.org/docrep/i9166e/i9166e_Chapter8_Fish_seafood.pdf

**Omasaki SK, Janssen K, Besson M, Komen H.** 2017. Economic values of growth rate, feed intake, feed conversion ratio, mortality and uniformity for Nile tilapia. Aquaculture **481,** 124-32.
https://doi.org/10.1016/j.aquaculture.2017.04.013

**OECD.** 2018; Food and Agriculture Organization of the United Nations (FAO). Chapter 8. Fish and seafood. In OECD/FAO Agricultural Outlook 2018–2027; FAO: Rome, Italy, p 175–190.
http://www.fao.org/docrep/i9166e/i9166e_Chapter8_Fish_seafood.pdf

**Oyebande L, Amani A, Mahé G, Niang-Diop I.** 2002. Climate change, water and wetlands in West Africa: Building linkages for their integrated Management. IUCN-BRAO Working Paper. Ouagadougou, Burkina-Faso.

**Oyinlola MA, Reygondeau G, Wabnitz CCC, Troell M, Cheung WWL.** 2018. Global estimation of areas with suitable environmental conditions for mariculture species. PLoS ONE **13,** 1–19.
https://doi.org/10.1371/journal.pone.0191086

**Pearce DW, Turner RK.** 1990. Economics of natural resources and the environment. London, Harvester Wheat sheaf, p 378

**Rapsomanikis G.** 2015. The economic lives of smallholder farmers. An analysis based on household data from nine countries. Food and Agriculture Organization of the United Nations, Rome, Italy.
http://www.fao.org/3/a-i5251e.pdf

**Robb DHF, MacLeod M, Hasan MR, Soto D.** 2017. Greenhouse gas emissions from aquaculture: a life cycle assessment of three Asian systems. FAO Fisheries and Aquaculture Technical Paper No. 609. Rome, FAO, p 110.

**Roy C, van der Lingen CD, Coetzee JC, Lutjeharms JRE.** 2007. Abrupt environmental shift associated with changes in the distribution of Cape anchovy Engraulis encrasicolus spawners in the southern Benguela. African Journal of Marine Science **29,** 309–319.
https://doi.org/10.2989/AJMS.2007.29.3.1.331

**Santos CF, Agardy T, Andrade F, Barange M, Crowder LB, Ehler CN, Orbach MK, Rosa R.** 2016. Ocean planning in a changing climate. Nature Geoscience **9,** 730.
https://doi.org/10.1038/ngeo2821

**Settele J, Scholes R, Betts R, Bunn S, Leadley P, Nepstad D, Overpeck JT, Taboada MA.** 2014. Terrestrial and inland water systems. In Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA, Cambridge University Press, p 271–359.
https://www.ipcc.ch/pdf/assessmentreport/ar5/wg2/WGIIAR5-Chap4_FINAL.pdf.

**Shelton C.** 2014. Climate change adaptation in fisheries and aquaculture – compilation of initial examples. FAO Fisheries and Aquaculture Circular No. 1088, Rome, FAO, p 34.
http://www.fao.org/3/a-i3569e.pdf

**Sherman M, Berrang-Ford L, Lwasa S, Ford J, Namanya DB, Llanos-Cuentas A, Maillet M, Harper S.** 2016. Drawing the line between adaptation and development: a systematic literature review of planned adaptation in developing countries. Wiley Interdisciplinary Reviews: Climate Change **7,** 707-726.
https://doi.org/10.1002/wcc.416

**Somerville C, Cohen M, Pantanella E, Stankus A, Lovatelli A.** 2014. Smallscale aquaponic food production. Integrated fish and plant farming. FAO Fisheries and Aquaculture Technical Paper No. 589. Rome, FAO, p. 262.
www.fao.org/3/a-i4021e.pdf

**Tacon AG, Metian M.** 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. Aquaculture **285,** 146-58.
https://doi.org/10.1016/j.aquaculture.2008.08.015

**Thaddeus CN, Chukwudumebi LE, Nnaemeka AC, Victoria CA.** 2012. Farmers' Perception of Climate Change Governance and Adaptation Constraints in Niger Delta Region of Nigeria, Africa Technology Policy Studies Network, Research Washington DC, US: InterAmerican Development Bank (IADB), p 7.

**Thoa NP, Ninh NH, Knibb W, Nguyen NH.** 2016. Does selection in a challenging environment produce Nile tilapia genotypes that can thrive in a range of production systems? Scientific reports **6**, 1-1.
https://doi.org/10.1038/srep21486

**Thomas G, O'Doherty D, Sterling D, Chin C.** 2010. Energy audit of fishing vessels. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment **224,** 87–101.
https://doi.org/10.1243/14750902JEME186

**Tran N, Chu L, Chan CY, Genschick S, Phillips MJ, Kefi AS.** 2019. Fish supply and demand for food security in Sub-Saharan Africa: An analysis of the Zambian fish sector. Marine Policy **99,** 343-50.
https://doi.org/10.1016/j.marpol.2018.11.009

**Troell M, Joyce A, Chopin T, Neori A, Buschmann AH, Fang JG.** 2009. Ecological engineering in aquaculture—potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture **297,** 1-9.
https://doi.org/10.1016/j.aquaculture.2009.09.010

**Troell M, Naylor RL, Metian M, Beveridge M, Tyedmers PH, Folke C, Arrow KJ, Barrett S, Crépin AS, Ehrlich PR, Gren Å.** 2014a. Does aquaculture add resilience to the global food system? Proceedings of the National Academy of Sciences **111**, 13257-63.
https://doi.org/10.1073/pnas.1404067111

**Troell M, Metian M, Beveridge M, Verdegem M, Deutsch L.** 2014b. Comment on 'Water footprint of marine protein consumption—aquaculture's link to agriculture'. Environmental Research Letters **9,** 109001.

**UN-DESA.** 2017. World Population Prospects: The 2017 Revision, Key Findings and Advance Tables; UN-DESA: New York, NY, USA.
https://esa.un.org/unpd/wpp/publications/files/wpp 2017_keyfindings.pdf

**Vejarano R, Siche R, Tesfaye W.** 2017. Evaluation of biological contaminants in foods by hyperspectral imaging: A review, International Journal of Food Properties **2,** 1264-1297.
https://doi.org/10.1080/10942912.2017.1338729

**Verdegem MCJ, Bosma RH.** 2009. Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. Water Policy **11,** 52-68.
https://doi.org/10.2166/wp.2009.003

**Waite R, Beveridge M, Brummett RE, Castine S, Chaiyawannakarn N, Kaushik S, Mungkung

R, Nawapakpilai S, Phillips M.** 2014. Improving productivity and environmental performance of aquaculture. Working Paper, Installment 5 of the Creating a Sustainable Future. World Resources Institute, Washington, DC.

**Wakchaure R, Ganguly S, Qadri K, Praveen PK, Mahajan T.** 2015. Importance of transgenic fish to global aquaculture: a review. Fisheries and Aquaculture Journal **6,** 4. http://dx.doi.org/10.4172/2150-3508.1000e124

**Wetengere K.** 2011. Socio-economic factors critical for intensification of fish farming technology. A case of selected villages in Morogoro and Dar es Salaam regions, Tanzania. Aquaculture International **19,** 33–49. https://doi.org/10.1007/s10499-010-9339-2

**Williams J, Crutzen PJ.** 2010. Nitrous oxide from aquaculture. Nature Geoscience **3,** 143. https://doi.org/10.1038/ngeo804

**World Fish Centre.** 2010. Barriers to Aquaculture Development as a Pathway to Poverty Alleviation and Food Security. Presentation by M. Beveridge, M. Phillips, P. Dugan and R. Brummett to the OECD Workshop, Paris.

**Yuan J, Xiang J, Liu D, Kang H, He T, Kim S, Lin Y, Freeman C, Ding W.** 2019. Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture. Nature Climate Change **9,** 318-22. https://doi.org/10.1038/s41558-019-0425-9