Environmental Management (2019) 63:159–172
https://doi.org/10.1007/s00267-018-1117-3

Global Aquaculture Productivity, Environmental Sustainability, and Climate Change Adaptability

Nesar Ahmed[1] · **Shirley Thompson**[1] · **Marion Glaser**[2]

Received: 11 May 2018 / Accepted: 29 October 2018 / Published online: 20 November 2018

Abstract
To meet the demand for food from a growing global population, aquaculture production is under great pressure to increase as capture fisheries have stagnated. However, aquaculture has raised a range of environmental concerns, and further increases in aquaculture production will face widespread environmental challenges. The effects of climate change will pose a further threat to global aquaculture production. Aquaculture is often at risk from a combination of climatic variables, including cyclone, drought, flood, global warming, ocean acidification, rainfall variation, salinity, and sea level rise. For aquaculture growth to be sustainable its environmental impacts must reduce significantly. Adaptation to climate change is also needed to produce more fish without environmental impacts. Some adaptation strategies including integrated aquaculture, recirculating aquaculture systems (RAS), and the expansion of seafood farming could increase aquaculture productivity, environmental sustainability, and climate change adaptability.

Keywords Aquaculture · Productivity · Environment · Climate change · Adaptation

Introduction

Aquaculture, the farming of fish, shellfish, and aquatic plants, is the fastest growing food production sector on earth. Global aquaculture production increased sixfold between 1990 and 2016, with an average annual growth rate of 5.8% during the period 2000–2016 (FAO 2018a). Excluding aquatic plants and non-food products (pearls and shells), global aquaculture production reached 80 million tons in 2016, with 54.1 million tons (68%) of finfish, 17.1 million tons (21%) of mollusks, 7.9 million tons (10%) of crustaceans, and 0.9 million tons (1%) of other aquatic animals (FAO 2018a). A total of 598 aquatic species were recorded in inland, coastal, and marine aquaculture[1]. Globally, inland aquaculture produced 51.4 million tons (64%), whereas both coastal aquaculture and mariculture (i.e., aquaculture in marine environments) produced 28.7 million tons (36%) in 2016 (FAO 2018a). Asia accounted for 89% of global aquaculture production in 2016 and China was the highest producer (61.5% of total production), followed by India, Indonesia, Vietnam, Bangladesh, Egypt, Norway, Chile, Myanmar, and Thailand (FAO 2018a). Globally, aquaculture predominates in tropical and subtropical regions, but it is also practiced in temperate regions.

Aquaculture has been playing a key role in increasing food production for human nutrition and food security

✉ Nesar Ahmed
nesar.ahmed@umanitoba.ca

[1] Natural Resources Institute, University of Manitoba, Winnipeg, Manitoba R3T 2M6, Canada

[2] Leibniz Center for Tropical Marine Research, Bremen 28359, Germany

---

[1] Aquaculture is practiced in three different water environments: (1) freshwater, (2) brackish water, and (3) seawater. Regardless of water environments, aquaculture can be divided into: (1) single species monoculture, (2) multiple species polyculture, and (3) integrated aquaculture with agriculture. Based on culture intensity as well as farming inputs (seed, feed, and fertilizer), aquaculture can be classified into: (1) extensive, (2) semi-intensive, and (3) intensive.

(Béné et al. 2016). Global per capita fish consumption reached 20.3 kg in 2016 and fish provide over 3.2 billion people worldwide with 20% of their animal protein intake (FAO 2018a). The production of carp, catfish, and tilapia has increased remarkably in Asia for local and regional consumption. Catfish and tilapia have also been exported to international markets. The culture of salmon, shrimp[2], and other high-value species for international trade has also developed. In fact, the rapid development of aquaculture has been considered part of the "blue revolution" (Simpson 2011).

Despite aquaculture growth, the challenge remains of feeding a global population that is currently increasing by 83 million per year and expected to increase from 7.6 billion in 2017 to 9.8 billion in 2050 (United Nations 2017). Thus, global food production needs to increase by 25–70% by 2050 (Hunter et al. 2017). At the same time, 5–7 million ha (0.6%) of global farmland are lost annually as a result of industrialization and urbanization (WWDR4 2012). Continuing population and food consumption growth with increased competition for land, water, and energy has already affected food production (Godfray et al. 2010).

Aquaculture production must be increased to meet the demand for food from a growing global population. It is estimated that 62% of food fish will need to be produced from aquaculture by 2030 to fill the gap between supply and demand with rapidly expanding global fish demand and relatively stable capture fisheries (World Bank 2013). Global capture fisheries have stagnated over the last two decades, reached 90.9 million tons in 2016, of which 79.3 million tons (87%) was from marine fisheries and 11.6 million tons (13%) from inland fisheries (FAO 2018a). Global capture fisheries are expected to remain stable at around 93 million tons during 2010–2030 (World Bank 2013). To meet expected demand for fish, global aquaculture production will need to increase to 109 million tons in 2030 (FAO 2018a), and 140 million tons in 2050 (Waite et al. 2014).

Aquaculture is highly dependent on the climate, and thus, climate change is a threat to increase global fish production. Climate change has already affected aquaculture ecosystems and production (Brander 2007; De Silva and Soto 2009). Water shortages in many parts of the world as a result of climate change affect food production by rising water demand and decreasing freshwater availability (Hanjra and Qureshi 2010; Turral et al. 2011). The impacts of climate change on crop productivity could affect food availability, stability, access, and utilization, and thus, undermine global food security (Schmidhuber and Tubiello 2007; Wheeler and von Braun 2013). Climate change is one of the challenges to achieving zero hunger[3] by 2030, which is one of the United Nations sustainable development goals (FAO 2018b). Considering the vulnerability of food fish production to the effects of climate change, adaptation strategies must cope with the challenges.

This article reviews environmental concerns for increasing aquaculture production in relation to climate change. The aim of this article is to highlight key issues for minimizing environmental effects and the likely impacts of climate change on aquaculture. Finally, this paper provides some adaptation options for increasing aquaculture production and climate change adaptation.

Environmental Concerns in Aquaculture

Aquaculture has been associated with a wide range of environmental concerns (Naylor et al. 2000 and 2005; Hall et al. 2011). If growth of global fish production continued at a strong pace, aquaculture could have detrimental environmental effects (Table 1). The following sections outline various environmental challenges in aquaculture.

Resource Decline

Increased aquaculture production will result in significant resource constraints due to limited land and freshwater resources. Globally, aquaculture covered 18.8 million ha of land (12.8 million ha inland and 6 million ha coastal) in 2010, which will occupy an estimated 44 million ha in 2050 (Waite et al. 2014). Additional land use impacts will be from terrestrial feed ingredients for aquafeed (i.e., feed for aquaculture) production. In 2010, aquaculture indirectly used 26.4 million ha of land for growing aquafeeds, which will increase to 61.6 million ha in 2050 (Waite et al. 2014).

Competition for freshwater use between agriculture and aquaculture is rapidly increasing. Globally, aquaculture utilized 201 km^3 of freshwater in 2010, set to increase to 469 km^3 in 2050 (Mungkung et al. 2014). Although aquaculture uses non-consumptive[4] water (Halwart and van Dam 2006), the water footprints for aquaculture include water losses through evaporation and infiltration (Verdegem and Bosma 2009). Moreover, global water footprint of commercial aquafeed production was 31–35 km^3 in 2008 (Pahlow et al. 2015), which will increase due to increased aquafeed production from 29.2 million tons in 2008 to 71

---

[2] After being the most traded product in fish for decades, shrimp now ranks second in terms of value after salmon (including trout), whereas carp is the most dominant group of aquaculture fish in terms of volume (FAO 2018a).

[3] The World Food Day on October 16, 2018 by the Food and Agriculture Organization of the United Nations highlighted "a zero hunger world by 2030 is possible" (FAO 2018b).

[4] Water is still available for other uses due to not consuming water.

Table 1 Major environmental challenges for increasing aquaculture production

Element	Environmental challenge	Reference
Aquaculture	Global aquaculture production will need to reach 140 million tons in 2050	Waite et al. (2014)
Capture fisheries	Global capture fisheries will likely be stable at 93 million tons by 2030	World Bank (2013)
Land requirement	Aquaculture will occupy 44 million ha of land in 2050	Waite et al. (2014)
Water demand	Aquaculture will use 469 km^3 of freshwater in 2050	Mungkung et al. (2014)
Freshwater eutrophication	Aquaculture-related freshwater eutrophication will reach 0.89 million tons P eq. in 2050	Waite et al. (2014)
Marine eutrophication	Aquaculture-related marine eutrophication will reach 3.2 million tons N eq. in 2050	Mungkung et al. (2014)
Nutrient release	Nutrient release from mariculture will increase up to sixfold by 2050	Bouwman et al. (2013)
Biotic depletion	Demand for wild fish to produce fishmeal and fish oil for aquafeeds will need 47 million tons in 2050	Waite et al. (2014)
Greenhouse gas (GHG) emissions	Aquaculture-related GHG emissions will reach 776 million tons CO_2e in 2050	Mungkung et al. (2014)

million tons in 2020 (Tacon et al. 2011). Non-fed mariculture (mollusks and seaweeds) could help release pressure on increasingly scarce freshwater resources.

Habitat Destruction

Converting low-lying rice fields and wetlands to fishponds is a common practice in many Asian countries (Bangladesh, China, and Vietnam) since it is more profitable (Edwards 2015). There is irreversible habitat destruction due to the widespread conversion of rice fields and wetlands to fish farms, affecting a great variety of flora and fauna, including aquatic plants, birds, crabs, fish, frogs, mussels, snails, and turtles. Habitat alteration as a result of land use change to aquaculture is likely to have negative impacts on biodiversity (Diana 2009).

Coastal aquaculture including shrimp farming is one of the key reasons for mangrove deforestation. Globally, shrimp farming expanded rapidly in the 1980s and 1990s, mainly in the tropics and subtropics (Lebel et al. 2002; Primavera 2006). Unplanned and unregulated shrimp farming caused widespread destruction of mangroves in Bangladesh, Brazil, China, India, Indonesia, Malaysia, Mexico, Myanmar, Sri Lanka, the Philippines, Thailand, and Vietnam (FAO 2007; UNEP 2014). Globally, 1.89 million ha of mangrove forests have been lost to coastal aquaculture, of which 1.4 and 0.49 million ha is from shrimp and other forms of aquaculture, respectively (Valiela et al. 2001). Mangrove deforestation by coastal aquaculture threatens ecosystem goods and services as mangroves are ecologically and economically important forests, which provide biodiversity conservation, coastal protection, and fisheries production (FAO 2007; UNEP 2014). The conversion of ecologically sensitive mangrove forests to shrimp farms has widespread environmental impacts, which must be avoided.

Water Pollution and Eutrophication

The application of antibiotics, fertilizers, and hormones in intensive aquaculture can contribute to water pollution. Overstocking and overfeeding of fishponds can produce organic matter and fish waste that reduce water quality. The inputs of chemical fertilizers (e.g., urea and triple super phosphate) and organic manure in aquaculture implies an increase of nitrogen (N) and phosphorus (P) in effluents. In 2010, the mean water pollution for global aquaculture production was 76 kg P/ton and 273 kg N/ton edible protein (Waite et al. 2014).

Aquaculture is an increasingly impactful source of nutrient pollution, known as eutrophication. The risk of harmful algal blooms (red tide) increases through aquaculture, which may cause massive fish kills. Economic loss from a single harmful algal bloom fish-kill event was estimated at US$330 million in Japan (Furuya et al. 2010). Aquaculture is expected to increase freshwater eutrophication from 0.38 million tons in 2010 to 0.89 million tons P eq. in 2050 (Waite et al. 2014). Aquaculture-related marine eutrophication is also set to increase from 1.4 million tons in 2010 to 3.2 million tons N eq. in 2050 (Mungkung et al. 2014). According to Bouwman et al. (2013), nutrient release from mariculture will increase up to sixfold by 2050. Thus, solutions to water pollution and eutrophication are needed to increase future aquaculture production while reducing environmental degradation.

Biotic Depletion

Although aquaculture has been advocated as a solution to overfishing, it is also one of the reasons for declining wild fish populations. The capture of wild broodstock and seedstock for aquaculture has detrimental effects on wild fish populations. Hatchery operations of prawn in

Bangladesh depend on high quality wild broodstock collection that can lead to biotic depletion (Ahmed and Troell 2010). Some aquaculture operations depend on wild-caught seed; for examples, eels in Europe and Japan, groupers in Southeast Asia, milkfish in Indonesia and the Philippines, shrimp in South Asia and parts of Latin America, tunas in South Australia, and yellowtails in Japan (Naylor et al. 2000; Ottolenghi et al. 2004). The use of wild-caught seed for capture-based aquaculture with high levels of bycatch has severe effects on wild fish populations (Ottolenghi et al. 2004; Primavera 2006; Ahmed and Troell 2010). It is, therefore, necessary to reduce bycatch from wild-caught seed to promote environmentally sound aquaculture practices.

One of the long-standing debates in salmon aquaculture is the use of fishmeal and fish oil[5] in aquafeeds, which is expressed as "Fish In–Fish Out (FIFO)" ratio. FIFO values for salmon aquaculture range from 2.3 to 4.9 (Tacon and Metian 2008; Jackson 2009), meaning that 2.3–4.9 kg of wild fish is required to produce 1 kg of salmon. Increased farmed salmon production has not resulted in decreased capture of wild salmon (Naylor et al. 2000; FAO 2018a), meaning that aquaculture is not an alternative but a complement to capture fisheries. FIFO values of eel, shrimp, and trout aquaculture are 3.1, 1.3, and 2, respectively (Jackson 2009). The demand for wild fish to produce fishmeal and fish oil for aquaculture will increase from 20.2 million tons in 2010 to 47.2 million tons in 2050 (Waite et al. 2014), which can lead to biotic depletion.

Ecological Effects

Aquaculture has adverse impacts on some ecosystem functions. The construction of fish farms near rivers has modified the hydrological patterns in many parts of the world with impacts on regional ecosystems (Martinez-Porchas and Martinez-Cordova 2012). Coastal aquaculture can also lead to saltwater intrusion with detrimental effects on freshwater ecosystems. Cage aquaculture releases untreated nutrients and chemicals into marine environments, with ecological effects. The escape of farmed salmon from net-pens can have genetic and ecological threats to wild salmon populations through competition and interbreeding (Naylor et al. 2005). Spawning in the wild for escaped farmed salmon has limited success as their offspring face high mortality (Hindar et al. 2006).

Reliance on exotic fish species in aquaculture has been gradually increasing over the years (Naylor et al. 2001; De Silva et al. 2009). The introduction and frequent escape of exotic fish species pose severe threats to native species due to competition for food and habitat. The escape of non-native aquaculture species can create "biological contamination" with unpredictable and irreversible ecological impacts (Naylor et al. 2001). In fact, invasive alien species in aquaculture can have negative impacts on biodiversity (De Silva et al. 2009). Most exotic species in aquaculture are considered invasive, and thus, precautionary measures must be taken to protect ecological effects.

Fish Disease and Parasite

The rapid development of aquaculture with presence of toxins and poor water quality are major causes of disease outbreaks. Disease has destroyed shrimp farming in many Asian countries because of environmental degradation (FAO 2018a). A variety of diseases are found in shrimp farming, including black spot, gill diseases, soft shell, tail rot, and white spot. Massive loss of shrimp production has been experienced with an early mortality syndrome, caused by vibrio bacteria (Boonyawiwat et al. 2017). Disease can cause huge shrimp mortality within a week, and thus, many aquaculture farms are abandoned (Primavera 2006; Bournazel et al. 2015). Epizootic ulcerative syndrome has also a great concern in aquaculture, which can cause mass mortalities. Better management practices are needed for long-term biosecurity management in aquaculture.

Intensive aquaculture can create environmental conditions for parasite growth and transmission from farmed to wild fish. Salmon aquaculture accelerates parasite growth and infestation in the seawater environment. Sea lice have the greatest impact on salmon farming and also threaten wild salmon and trout fisheries (Torrissen et al. 2013). Sea lice parasitism in salmon aquaculture caused damages of US $436 million to the Norwegian industry in 2011 (Abolofia et al. 2017). Tackling sea lice is therefore a key concern for the salmon industry.

Greenhouse Gas (GHG) Emissions

The growth of aquaculture has increased GHG emissions. Including land use change, average GHG emissions from aquaculture were estimated at 2.12 kg CO_2e/kg live weight of carps in India, 1.81 kg CO_2e/kg live weight of Nile tilapia in Bangladesh, and 1.61 kg CO_2e/kg live weight of striped catfish in Vietnam (Robb et al. 2017). GHG emissions from aquaculture will increase from 332 million tons in 2010 to 776 million tons CO_2e in 2050 (Mungkung et al. 2014). Aquafeeds are considered the largest source of GHG emissions in aquaculture because of the production and transportation of raw materials, energy use in feed mills, and high feed conversion ratio (Robb et al. 2017).

---

[5] Fish oil is extracted from fish while producing fishmeal. To prepare aquafeeds, the demand of fish oil is lower than fishmeal as only a few species require fish oil. The fish oil is a good source of nutrition, which provides of a smell to the feed (Robb et al. 2017).

Mangrove deforestation through coastal aquaculture releases significant amounts of blue carbon[6] as mangroves are the most carbon-rich forests in the tropics (Pendleton et al. 2012; Siikamäki et al. 2012; Alongi 2014). Mangroves stock about 3–4 times more carbon than tropical forests (Donato et al. 2011). Clearing mangroves to build shrimp farms discharges considerable amounts of blue carbon and reduces storage capacities. On average, the loss of blue carbon from the transformation of mangroves to shrimp ponds is 554 tons/ha (Kauffman et al. 2017). Blue carbon storages of redundant shrimp farms are only ~11% that of mangroves (Kauffman et al. 2014). The aboveground carbon receive in shrimp farms is 91% less than that of intact mangrove forests (Kauffman et al. 2017). Carbon emissions along with other GHG (CH_4, N_2O) have been the leading cause of climate change (IPCC 2014). It is, therefore, vital to reduce GHG emissions from aquaculture to confront anthropogenic climate change.

Impacts of Climate Change on Aquaculture

The survival, growth, and production of fish in aquaculture is highly susceptible to environmental concern as well as climate change (Fig. 1). Aquaculture production is often at risk from a combination of climatic variables, including cyclone, drought, flood, global warming, ocean acidification, rainfall variation, salinity, and sea level rise (Brander 2007; De Silva and Soto 2009; Ahmed and Diana 2015). Changes in these climatic factors could have severe effects on future aquaculture production (Table 2). Global marine primary production will decline by 6% by 2100 due to climate change (Kwiatkowski et al. 2017), which may undermine future seafood production.

Cyclone

Tropical cyclones are the most destructive natural hazards to coastal aquaculture in low-lying territories those are poorly protected against tidal surges. Water quality of fish farms deteriorates after cyclones because of erosion, saltwater intrusion, and pollution. A large volume of pollutants enters into shrimp farms with tidal surges. Mariculture including salmon farming is also vulnerable to cyclones because of devastating effects on net-pen and cage culture. El Niño[7] associated cyclones in Chile often damage the salmon industry greatly, resulting in massive escape of farmed salmon to the wild (Soto et al. 2001). Cyclones may increase occurrence of aquaculture stocks escaping into open-water, threatening biodiversity and ecosystems (De Silva and Soto 2009). Intense rainfall with massive wind associated tropical cyclones are likely to increase in South and Southeast Asian countries, those are dominant in global aquaculture production (Barange and Perry 2009). The intensity of tropical cyclones will increase by 2–11% by 2100 (Knutson et al. 2010), which may undermine future aquaculture production.

Drought

Drought is one of the key constraints in inland aquaculture. The occurrence and intensity of droughts has increased due to climate change as global warming can lead monsoon to turn into dry mode, resulting in considerable declines in precipitation (Conway and Waage 2010). Over 25% of the earth will face severe drought by 2050 if global temperature increases 2 °C (Park et al. 2018). Water demand for inland aquaculture will increase due to severe drought. Prolonged drought is also concerned for freshwater aquaculture because of reducing groundwater levels. Seasonal drought as a result of low precipitation and high evaporation often causes in short aquaculture period. Year-round fish production is not feasible due to severe or prolonged droughts and fish become anxiety in low volume of water. Drought also aggravates the concentration of waste metabolites (ammonia, CO_2, and nitrites) and salinity in fishponds and shrimp farms that affects aquaculture production.

Flood

Floods appear to become extreme due to climate change (Conway and Waage 2010). Intense rainfall during the monsoon as well as erratic precipitation causes a greater frequency of floods. Sudden or prolonged floods cause physical damage to aquaculture infrastructure including fish farms. Inland aquaculture is greatly susceptible to flooding as preventing escape of fish from ponds and entering predatory fish from wild is very difficult during floods. River erosion can also intensify the effects of flooding, which may threaten cage aquaculture in rivers. Water level rise during rainy season as well as sea level rise in the Mekong Delta, Vietnam seriously affect striped catfish farming (Nguyen et al. 2014). Coastal flooding could also increase due to high river discharge, low drainage capacity, and backwater effects from seas and oceans. The frequency of coastal flooding will be doubled by 2050 due to sea level rise (Vitousek et al. 2017). Coastal flooding could affect brackish water aquaculture, including shrimp cultivation.

---

[6] Carbon in coastal and marine ecosystems is known as blue carbon, which is stored, sequestered, and released from mangroves, salt marshes, and seagrasses.

[7] El Niño is a climate cycle in the Tropical Pacific Ocean with warm temperatures.

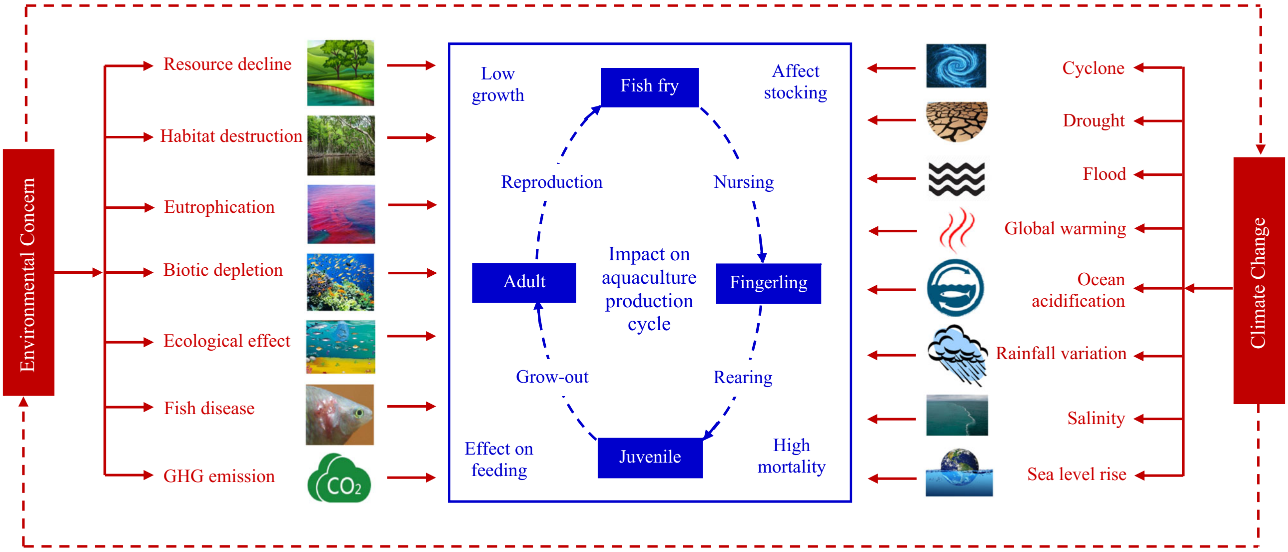

Fig. 1 Environmental concern and climate change in aquaculture (red colors) with possible impact on aquaculture production cycle (blue colors)

Table 2 Potential changes in climatic factors those could affect future aquaculture production

Climatic factor	Potential change	Reference
Cyclone	Intensity of tropical cyclones will increase 2–11% by 2100	Knutson et al. (2010)
Drought	Over 25% of the earth will face severe drought by 2050	Park et al. (2018)
Flood	The frequency of coastal flooding will be doubled by 2050	Vitousek et al. (2017)
Global warming	Global temperature is likely to increase 4 °C by 2100	IPCC (2014)
Ocean acidification	Ocean acidification could be doubled or tripled by 2100	Dupont and Pörtner (2013)
Rainfall variation	Rainfall erosivity may increase by 17–18% in Europe and the USA by 2050	Nearing et al. (2004); Panagos et al. (2017)
Salinity	Sea surface salinity will considerably change by 2050	Durack (2015)
Sea level rise	Sea level could rise 0.15–0.38 m by 2050	Sweet et al. (2017)

Global Warming

Water temperature in tropical and sub-tropical regions may have increased in recent years as a result of global warming, which could have severe effects on fish production. Global mean temperature could increase 4 °C by 2100 (IPCC 2014). Increases in water temperature could exacerbate multiple effects including changes in ecosystem functioning of freshwater ponds (Woodward et al. 2010). According to Ficke et al. (2007), a little increase in water temperature (1–2 °C) can cause sub-lethal physiological effects on tropical fish. A rise of water temperature over 17 °C would be harmful for salmon aquaculture (De Silva and Soto 2009). Sea surface temperature (SST) could also increase due to the effect of GHG as well as global warming (IPCC 2014). Increase in SST could intensify the incidence of toxic algal blooms and red tides that pose a risk to seafood production (Peperzak 2003; De Silva and Soto 2009). Global warming and subsequent increase in water temperature including SST could have dramatic effects on future aquaculture production.

Ocean Acidification

Climate change causes ocean acidification that is sometimes called “climate change’s equally evil twin” due to its harmful consequence of CO_2 in the atmosphere that also affect underwater life[8]. Ocean acidification is the consequence of rising atmospheric CO_2 that is absorbed by the oceans resulting in low water pH. Ocean acidification will reduce water pH of 0.3–0.4 from 8.2 to 7.8 by 2100 (Feely et al. 2009; Williamson and Turley 2012). It is predicted that ocean acidification could be doubled or tripled by 2100 (Dupont and Pörtner 2013), which could affect future

---

[8] “Life below water” is one of the sustainable development goals by the United Nations, aiming to conserve and sustainably use the seas, oceans, and marine resources.

seafood production. The impacts of ocean acidification on mariculture has received recent attention. Ocean acidification has negative effects on finfish, seaweed, and shellfish production in North America (Clements and Chopin 2017), undermining shell formation of mussels and oysters in mariculture (De Silva and Soto 2009). According to Kroeker et al. (2013), ocean acidification has adverse effects on calcification, development, and growth of a range of calcified marine organisms.

Rainfall Variation

Climate change affects rainfall intensity and variability with adverse effects on fish productivity. Annual rainfall is likely to decrease in Mediterranean Africa, the Northern Sahara, and Southern Africa (Barange and Perry 2009), which could reduce aquaculture opportunities in these regions. Water availability in fishponds varies greatly with rainfall variation that has also increased the risk of flood and drought. Early or late rainfall with sudden intense rain can cause devastation on inland and coastal aquaculture. Heavy rainfall also causes erosion and water turbidity, reducing fish productivity. By 2050, climate change may increase rainfall erosivity[9] by 17% in the USA (Nearing et al. 2004) and 18% in Europe (Panagos et al. 2017). Abnormal patterns of rainfall could affect salinity variation in brackish water aquaculture. Low rainfall could increase the concentration of salinity in coastal aquaculture with adverse effects on brackish water ecosystems. Ultimately, rainfall variation potentially undermines aquaculture production (De Silva and Soto 2009).

Salinity

Changes in water salinity have dramatic effects on aquaculture productivity. Low freshwater discharge from rivers, high evaporation, inadequate precipitation, sea level rise, and storm surges tend to play a key role in rising coastal salinity. Changes in ocean salinity indicate a number of climate change processes, including evaporation, ice melting, rainfall variation, and river runoff (Barange and Perry 2009). The biodiversity of freshwater ecosystems is sensitive to salinity, and saltwater intrusion into freshwater ponds affects soil fertility and water quality which considerably declines fish productivity. Changes in salinity with temperatures in coastal environments also influence aquaculture production (De Silva and Soto 2009). Water salinity fluctuations over a certain range could result in transmission of white spot syndrome virus to shrimp (Liu et al. 2006). Globally, sea surface salinity (SSS) will change significantly by 2050 due to climate change (Durack 2015). Increased SSS will affect seafood productivity as most marine species are stenohaline with tolerance of 30–40 ppt salinity (Kültz 2015).

Sea Level Rise

Because of global warming and glacier melting, sea level has been rising at an alarming rate of 3.7 mm/year, which will be 11 mm/year during 2081–2100 (Church et al. 2013). Global sea level could rise 0.15–0.38 m by 2050 (Sweet et al. 2017), and 0.8–1.5 m by 2100 (Kopp et al. 2017). Sea level rise has been threatening many low altitude regions, including Asian mega-deltas, the Atlantic and Gulf of Mexico coasts of the USA, the Baltic, the Caribbean, the Mediterranean, small island regions, and other low-lying coastal areas (Nicholls et al. 2007). Although global sea level rise is not geographically equal due to its relation to regional ocean circulation processes, all coastal aquaculture ecosystems are vulnerable to sea level rise (Barange and Perry 2009). Coastal aquaculture is gradually at risk from sea level rise due to increased exposure of coastal ecosystems to tidal surges. Sea level rise could have multiple impacts on biotic, ecological, and habitat (mangroves, marshes, and wetlands) changes, thereby affecting aquaculture practices (De Silva and Soto 2009). Future sea level rise could have severe impacts on global fish production.

Adaptation to Climate Change

Adaptation to climate change is needed to produce more fish without environmental impacts. Aquaculture production must increase sustainably, whereas its environmental impacts must reduce considerably. A conceptual framework has been developed for increasing aquaculture production, reducing environmental degradation, and climate change adaptation (Fig. 2). Proposed adaptation strategies to climate change seems to increase aquaculture production with environmental sustainability (Table 3).

Integrated Aquaculture

Integrated aquaculture is an approach of integrated resource management, which enhances natural resource use efficiency for increasing productivity, profitability, and sustainability (Pant et al. 2004; Nhan et al. 2007; Dey et al. 2010). Integrated aquaculture is a form of sustainable intensification for producing more food from the same area of land and water without or less environmental impacts (Godfray et al. 2010). Sustainable intensification is vital for adapting to climate change as both are closely interlinked concepts (Campbell et al. 2014). Integrated rice-fish

---

[9] Rainfall erosivity is an erosive power of rainfall to cause soil erosion or loss by water.

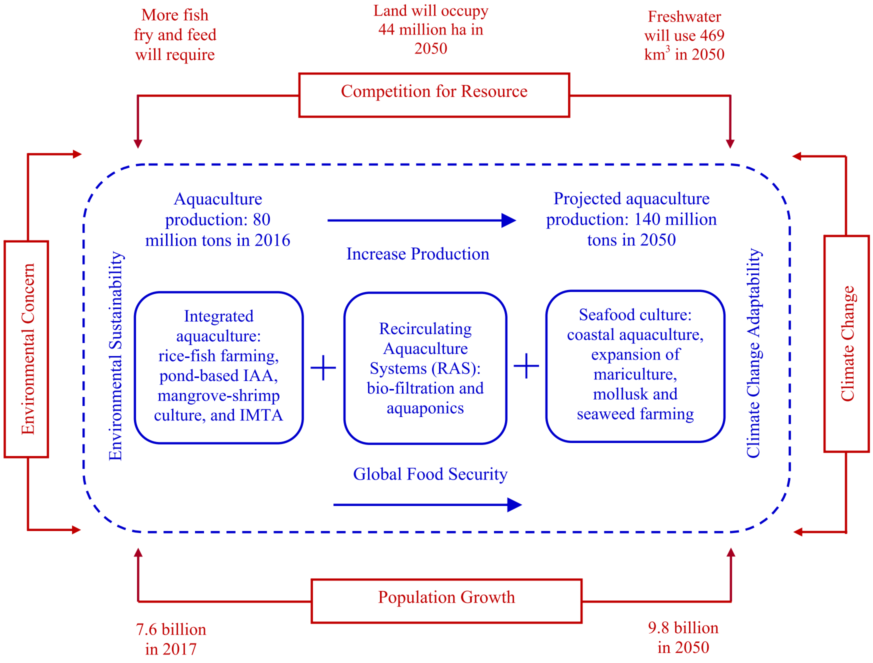

Fig. 2 A conceptual framework to increase aquaculture production in relation to environmental concern and climate change; red colors illustrate environmental constraint and climate change with resource competition and population growth those could affect future aquaculture production; blue colors demonstrate possible adaptation strategies to climate change for increasing aquaculture productivity, environmental sustainability, and food security

farming is ecologically sound due to improving soil fertility and water quality through generating N and P with integrated pest management by fish, which in turn reduces the application of fertilizers and pesticides (Halwart and Gupta 2004). Rice-fish farming also increases the rice yield by 8% due to presence of fish (Mohanty et al. 2004). Integrated prawn-rice-fish farming in Bangladesh can adapt to climate change as community-based flood control devices (dams, embankments) and the creation of higher dikes around rice fields can protect from inundation (Ahmed et al. 2014). Pumping groundwater with irrigation may alleviate water shortage and high water temperature in dry season rice-fish culture. Rainwater harvesting in small reservoirs and supplementary irrigation of rice field can play a key role in increasing food production and climate change adaptation (Wisser et al. 2010). Salt-tolerant rice varieties and rice-fish culture in Vietnam can reduce vulnerability to storm surges and sea level rise (Shelton 2014).

Integrated aquaculture–agriculture (IAA) is also efficient to produce more food due to using nutrient-rich pond mud and water to manure fruit trees (e.g., banana, coconut, guava, lemon, and papaya) and vegetables (bean, cucumber, and gourd) on pond dikes. On average, pond-based IAA is 11% more productive than non-IAA in Malawi (Dey et al. 2010). Integrated farming could also reduce risks of crop failure due to harvesting in different seasons. Moreover, modern polyculture of 6–8 carp species in China contributes to productivity increases from 12–15 tons/ha/year to 30–40 tons/ha/year (Miao and Yuan 2007). Polyculture of filter-feeding and herbivore fish species can use natural feeds (aquatic plants and planktons) to improve farm productivity and reduce feed-related water pollution. The impacts of climate change on pond-based IAA could be reduced as fruit trees on higher pond dikes could lower erosion and flood protection during the rainy season. In Bangladesh, vegetable crops on pond slopes and aquatic weeds in ponds can provide shade and shelter for fish during hot summer to reduce thermal stress (Ahmed and Diana 2016).

Integrated mangrove-shrimp farming, known as silvo-aquaculture or silvo-fisheries, is an environmentally friendly aquaculture practiced in Indonesia, Malaysia, the Philippines, Thailand, and Vietnam (Primavera et al. 2000; Ha et al. 2012; Bosma et al. 2016). One of the adaptation strategies to compensate for mangrove deforestation by shrimp cultivation in Southeast Asian countries is to develop silvo-aquaculture for the conservation and rehabilitation of mangroves (Primavera et al. 2000). Integrated mangrove-shrimp cultivation has potential to sequester blue carbon (Ahmed et al. 2018). Mangrove restoration could also plays a significant role in mitigating climate change by sequestering and storing blue carbon (Donato et al. 2011; Irving et al. 2011; Mcleod et al. 2011; Pendleton et al. 2012). Mangrove reforestation surrounding shrimp farms is suggested in Vietnam to capture and store carbon for climate change mitigation (Bui et al. 2014). Rehabilitating mangroves in abandoned shrimp ponds of Panay Island, the Philippines could help climate change mitigation and adaptation (Duncan et al. 2016). In addition to protecting shrimp farms, mangrove restoration could increase social and ecological resilience to climate change as mangroves are significant in providing protection from coastal flooding, cyclones, shoreline erosion, saltwater intrusion, sea level rise, and tidal surges (Baird et al. 2009; Duarte et al. 2013).

Table 3 Strategies for increasing aquaculture production, reducing environmental degradation, and adaptation to climate change

Strategy	Environmental sustainability	Climate change adaptation
Integrated farming	Integrated rice-fish farming is ecologically sound to increase productivity with reduced fertilizer and pesticide use	Community-based flood control and irrigation facilities may help rice-fish culture
	Pond-dike cropping with polyculture can increase productivity with efficient resource use	Dike cropping could lower erosion, flood protection, and shade fish to reduce thermal stress
	Integrated mangrove-shrimp cultivation can help mangrove restoration for sustainable shrimp production	Mangrove restoration can increase carbon sequestration with protection from extreme weather
	IMTA is an ecosystem-based approach to increase production for creation of balanced environment	IMTA could increase resilience to climate change due to its tolerance to climatic factors
Recirculating aquaculture systems (RAS)	RAS are environmentally friendly, which filter the water for reusing fish production	Controlled environment of RAS are not directly affected by climate change
	Year-round RAS produce large amounts of fish in a relatively low volume of water	Brackish water RAS can be an option for adaptation to climate change in coastal aquaculture
	Aquaponics provide mutually beneficial environment to increase production	Aquaponics can practice in greenhouse systems without affecting climate change
Seafood culture	Ecosystem-based coastal aquaculture in brackish water resources can increase productivity with efficient resource use	Integrated coastal management with disaster preparedness can improve resilience to climate change
	Ecosystem approach to mariculture could increase seafood production and environmental benefits	Marine species can adapt to climate change through shifting distributions and timing of biological events
	Without external feeding of mollusk and seaweed culture is environmentally friendly due to reducing eutrophication and pollution	Mollusk and seaweed can adapt to change in salinity, and seaweed absorb carbon through photosynthesis

Integrated multi-trophic aquaculture (IMTA) is an ecosystem-based approach to culture fed-fish (finfish), organic extractive species (shellfish), and inorganic extractive species (seaweeds) from different trophic levels in an integrated farm to create balanced systems for environmental sustainability (Troell et al. 2009; Chopin 2011; Chopin et al. 2012). IMTA operates in over 40 countries on an experimental and commercial basis, including Canada, Chile, China, Japan, the USA, and many European countries (Chopin 2011). Utilizing local environmental and socioeconomic conditions, human innovations, and further technological development could help IMTA for responsible aquaculture practices in the future (Diana et al. 2013). Open-water IMTA in coastal and marine environments may not be affected by flood, drought, rainfall variation, and sea level rise. Shellfish and seaweeds tolerate a wide range of salinity, and thus, IMTA can adapt to changes in SSS. In IMTA, absorption of waste particles and nutrients by shellfish and seaweeds reduces mineralization and higher water temperature (Sreejariya et al. 2011), which can adapt to increased SST. Seaweeds in IMTA can also keep water cooler by absorbing pollutants and toxic elements. In IMTA, carbon sequestration is also possible by seaweeds through photosynthesis (Chung et al. 2013).

Recirculating Aquaculture Systems (RAS)

RAS are land-based indoor fish farms with closed containment rearing systems where biofiltration is needed to purify water and remove toxic metabolic wastes of fish (Bostock et al. 2010; Edwards 2015). RAS can be operated with fresh, brackish or marine water to filter and clean the water for recycling back to fish tanks. Reusing the water through mechanical or biological filters, RAS can be costly to install and operate but are environmentally friendly and highly productive. RAS usually produce large amounts of fish (500 tons/year) in a relatively low volume of water (4000 m^3) (Bregnballe 2015). RAS generally produce high-value fish (e.g., barramundi, salmon, shrimp, trout, and tuna) at high densities and year-round. RAS are mostly practiced in developed countries (Australia, Canada, Europe, and the USA) within a controlled environment, and thus, not directly affected by climate change. Coastal aquaculture with onshore tanks has developed in Iceland, South Korea, and Spain (Bostock et al. 2010), as these are unaffected by climate change.

Aquaponics combine aquaculture and hydroponics for producing fish in a recirculation system and growing plants in nutrient water without soil (Bregnballe 2015). The fish waste in the water supplies nutrients to plants and microorganisms, which filter and clean the water that is returned to fish tanks. Aquaponics provide an interactive and mutually beneficial environment for fish and vegetable crops. Common aquaponics fish species are bass, bluegill, catfish, perch, tilapia, and trout, whereas common plant crops are basil, cucumber, lettuce, peppers, salad greens, and tomatoes (Love et al. 2015). Aquaponics has been practiced in over 43 countries around the world (Love et al. 2014). Typically, aquaponics are 10 times more productive than conventional agriculture, and use 85–90% less water than traditional irrigation (INMED 2011). Aquaponics can be practiced as greenhouse systems without climate implications.

Seafood Culture

The further expansion of coastal aquaculture can help to produce much needed extra food for a growing global population. The expansion of coastal aquaculture with environmentally sustainable practices and appropriate adaptation strategies can increase fish production. Comparatively unexploited brackish waters in Africa and Latin America could be utilized for coastal aquaculture (Bostock et al. 2010). However, coastal aquaculture is more vulnerable to climate change than inland aquaculture due to severe effects by cyclones with tidal surges, salinity variation, and sea level rise. Nevertheless, integrated coastal management with infrastructure development (basin, dam, embankment, and irrigation) and disaster preparedness can improve resilience to climate change (Shelton 2014). Wider and stronger dikes with deeper ponds and changing water can adapt high water temperature, rainfall variation, and sea level rise for shrimp farming in the Mekong Delta, Vietnam (NACA 2012). The culture of mud crab in Vietnam is also more tolerant of salinity and better respond to sea level rise (Shelton 2014).

The stagnation of capture fisheries calls for an expansion of mariculture. Ecosystem approach to aquaculture including net-pen and cage culture in marine environment is one of the most promising practices for increasing seafood production. The future contribution of the oceans to increasing seafood production must be obtained from mariculture. However, globally 0.3 million km of coastline (44% of maritime nations) are not used for seafood production (Kapetsky et al. 2013). Thus, the expansion of onshore and offshore[10] seafood production is huge. In fact, the expansion of onshore and offshore mariculture for increasing seafood production is a possible solution to feed the growing global population (Duarte et al. 2009). Offshore mariculture can be extended within exclusive economic zone of marine nations (Kapetsky et al. 2013), which may require technological innovation for widespread adoption. Mariculture could increase resilience to climate change due to its tolerance to flood, drought, rainfall variation, and sea level rise. According to Miller et al. (2018), marine species can adapt to climate change through shifting distributions and timing of biological events. In response to increasing temperature, Pacific salmon has physiological and genetic capacity to increase its thermal tolerance (Muñoz et al. 2015).

Seafood production including mollusks and seaweeds will be predominantly sourced through mariculture by 2050 (Diana et al. 2013). The cultivation of bivalve mollusks (e.g., clams, mussels, oysters, and scallops) and seaweeds in long-line and raft methods has been rapidly growing worldwide in countries with history of mariculture (Bostock et al. 2010; FAO 2018a). Climate change can provide opportunity for mussel farming in the southern Baltic Sea (Klamt and Schernewski 2013). Ecological impacts of mollusk and seaweed farming are minimal as they can grow without external feeding. Mollusks and seaweeds in mariculture could reduce eutrophication by removing organic waste and nutrients. Chinese seaweed culture, for instance, annually removes about 75,000 tons N and 9500 tons P (Xiao et al. 2017). Seaweed culture can contribute to climate change mitigation and adaptation through carbon sequestration, reducing methane emissions, shoreline protection, and lowering ocean acidification, which in turn benefits shellfish production (Duarte et al. 2017). Seaweed farming along the southern coast of Korea can help for mitigation and adaptation against global warming (Chung et al. 2013).

Conclusions

To meet the demand for fish from a growing global population, aquaculture production must be increased due to stagnation of capture fisheries. However, aquaculture has generated a wide range of environmental challenges, and further environmental effects are likely if aquaculture production continue. Climate change is a further threat to global fish production. Higher aquaculture production is needed that is environmentally sustainable and can adapt to climate change.

Some adaptation strategies to climate change including integrated aquaculture, RAS, and the expansion of seafood production under coastal aquaculture and mariculture potentially increase fish production. Integrated rice-fish farming, pond-based IAA, and polyculture can increase fish production with reduced environmental impacts. Environmentally friendly integrated mangrove-shrimp cultivation with mangrove restoration could increase blue carbon sequestration and achieve climate change mitigation and adaptation. Moreover, IMTA, RAS, and the expansion of onshore and offshore mariculture could increase seafood

---

[10] Offshore mariculture could be operated over 2 km from shore, usually within continental shelf zones.

production, whereas reducing environmental impacts and adaptation to climate change.

The proposed aquaculture strategies significantly contribute to global fish production, whereas positively affecting both environmental sustainability and climate change adaptability. However, institutional support with technical and financial assistance is needed for implementing these strategies. Key stakeholders including international agencies, researchers, policymakers, government and non-governmental organizations, and fish farming communities need to collaborate for implementation of these strategies. Social, economic, and ecological challenges must also be identified and addressed to facilitate the proposed adaptation strategies. Empirical research is needed to understand interlinked processes of increasing aquaculture productivity, environmental sustainability, and climate change adaptability.

Acknowledgments The study was supported through the Alexander von Humboldt Foundation, Germany. The study was a part of the first author's research work under the Georg Forster Research Fellowship by the Alexander von Humboldt Foundation at the Leibniz Center for Tropical Marine Research (ZMT) in Bremen, Germany. The study was also linked to the first author's research at the Natural Resources Institute (NRI), University of Manitoba, Canada. An earlier draft of this paper was presented in March 2017 by the first author at the ZMT, Germany. We thank the audience for their positive encouragement. The views and opinions expressed herein are solely those of the authors and do not necessarily reflect the views of ZMT or NRI. We thank two anonymous reviewers for insightful comments.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Abolofia J, Asche F, Wilen JE (2017) The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. Mar Resour Econ 32:329–349

Ahmed N, Diana JS (2015) Threatening "white gold": impacts of climate change on shrimp farming in coastal Bangladesh. Ocean Coast Manag 114:42–52

Ahmed N, Diana JS (2016) Does climate change matter for freshwater aquaculture in Bangladesh? Reg Environ Change 16:1659–1669

Ahmed N, Troell M (2010) Fishing for prawn larvae in Bangladesh: an important coastal livelihood causing negative effects on the environment. Ambio 39:20–29

Ahmed N, Bunting SW, Rahman S et al. (2014) Community-based climate change adaptation strategies for integrated prawn-fish-rice farming in Bangladesh to promote social-ecological resilience. Rev Aquac 6:20–35

Ahmed N, Thompson S, Glaser M (2018) Integrated mangrove-shrimp cultivation: potential for blue carbon sequestration. Ambio 47:441–452

Alongi DM (2014) Carbon cycling and storage in mangrove forests. Annu Rev Mar Sci 6:195–219

Baird AH, Bhalla RS, Kerr AM et al. (2009) Do mangroves provide an effective barrier to storm surges? Proc Natl Acad Sci USA 106: E111

Barange M, Perry RI (2009) Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. In: Cochraneo K, De Young C, Soto D et al. (eds) Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge. FAO Fisheries and Aquaculture Technical Paper No. 530. Rome, pp 7–106

Béné C, Arthur R, Norbury H et al. (2016) Contribution of fisheries and aquaculture to food security and poverty reduction: assessing the current evidence. World Dev 79:177–196

Boonyawiwat V, Patanasatienkul T, Kasornchandra J et al. (2017) Impact of farm management on expression of early mortality syndrome/acute hepatopancreatic necrosis disease (EMS/AHPND) on penaeid shrimp farms in Thailand. J Fish Dis 40:649–659

Bosma RH, Nguyen TH, Siahainenia AJ et al. (2016) Shrimp-based livelihoods in mangrove silvo-aquaculture farming systems. Rev Aquac 8:43–60

Bostock J, McAndrew B, Richards R et al. (2010) Aquaculture: global status and trends. Philos Trans R Soc B 365:2897–2912

Bournazel J, Kumara MP, Jayatissa LP et al (2015) The impacts of shrimp farming on land-use and carbon storage around Puttalam lagoon, Sri Lanka. Ocean Coast Manag 113:18–28

Bouwman L, Beusen A, Glibert PM et al. (2013) Mariculture: significant and expanding cause of coastal nutrient enrichment. Environ Res Lett 8:044026

Brander KM (2007) Global fish production and climate change. Proc Natl Acad Sci USA 104:19709–19714

Bregnballe J (2015) A guide to recirculation aquaculture: an introduction to the new environmentally friendly and highly productive closed fish farming systems. FAO and EUROFISH International Organization, Copenhagen

Bui TD, Maier SW, Austin CM (2014) Land cover and land use change related to shrimp farming in coastal areas of Quang Ninh, Vietnam using remotely sensed data. Environ Earth Sci 72:441–455

Campbell BM, Thornton P, Zougmoré R et al. (2014) Sustainable intensification: what is its role in climate smart agriculture? Curr Opin Environ Sustain 8:39–43

Chopin T (2011) Progression of the integrated multi-trophic aquaculture (IMTA) concept and upscaling of IMTA systems towards commercialization. Aquac Eur 36(4):5–12

Chopin T, Cooper JA, Reid G et al. (2012) Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of feed aquaculture by extractive aquaculture. Rev Aquac 4:209–220

Chung IK, Oak JH, Lee JA et al. (2013) Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean project overview. ICES J Mar Sci 70:1038–1044

Church JA, Clark PU, Cazenave A et al. (2013) Sea level change. In: Stocker TF, Qin D, Plattner G-K et al. (eds) Climate Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge, UK, pp 1137–1216

Clements JC, Chopin T (2017) Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies. Rev Aquac 9:326–341

Conway G, Waage J (2010) Science and Innovation for Development. UK Collaborative on Development Sciences, London

De Silva SS, Soto D (2009) Climate change and aquaculture: potential impacts, adaptation and mitigation. In: Cochrane K, De Young C, Soto D et al. (eds) Climate Change Implications for Fisheries and Aquaculture: Overview of Current Scientific Knowledge. FAO Fisheries and Aquaculture Technical Paper No. 530, Rome, pp 151–212

De Silva SS, Nguyen TTT, Turchini GM et al. (2009) Alien species in aquaculture and biodiversity: a paradox in food production. Ambio 38:24–28

Dey MM, Paraguas FJ, Kambewa P et al. (2010) The impact of integrated aquaculture-agriculture on small-scale farms in Southern Malawi. Agric Econ 41:67–79

Diana JS (2009) Aquaculture production and biodiversity conservation. BioScience 59:27–38

Diana JS, Egna HS, Chopin T et al. (2013) Responsible aquaculture in 2050: valuing local conditions and human innovations will be key to success. BioScience 63:255–262

Donato DC, Kauffman JB, Murdiyarso D et al. (2011) Mangroves among the most carbon-rich forests in the tropics. Nat Geosci 4:293–297

Duarte CM, Holmer M, Olsen Y et al. (2009) Will the oceans help feed humanity? BioScience 59:967–976

Duarte CM, Losada IJ, Hendriks IE et al. (2013) The role of coastal plant communities for climate change mitigation and adaptation. Nat Clim Change 3:961–968

Duarte CM, Wu J, Xiao X et al. (2017) Can seaweed farming play a role in climate change mitigation and adaptation? Front Mar Sci 4:100

Duncan C, Primavera JH, Pettorelli N et al. (2016) Rehabilitating mangrove ecosystem services: a case study on the relative benefits of abandoned pond reversion from Panay Island, Philippines. Mar Pollut Bull 109:772–782

Dupont S, Pörtner H (2013) Get ready for ocean acidification. Nature 498:429

Durack PJ (2015) Ocean salinity and the global water cycle. Oceanography 28(1):20–31

Edwards P (2015) Aquaculture environment interactions: past, present and likely future trends. Aquaculture 447:2–14

FAO (2007) The World's Mangroves1980–2005. Food and Agriculture Organization of the United Nations, Rome

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

FAO (2018b) Our Actions are Our Future: A #ZeroHunger World by 2030 is Possible. Food and Agriculture Organization of the United Nations, Rome

Feely RA, Doney SC, Cooley SR (2009) Ocean acidification: present conditions and future changes in a high-CO_2 world. Oceanography 22:36–47

Ficke AD, Myrick CA, Hansen LJ (2007) Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fish 17:581–613

Furuya K, Glibert PM, Zhou M et al. (eds) (2010) Global Ecology and Oceanography of Harmful Algal Blooms in Asia: A Regional Comparative Program. IOC and SCOR, Paris and Newark, Delaware

Godfray HCJ, Beddington JR, Crute IR et al. (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818

Ha TTT, Bush SR, Mol APJ et al. (2012) Organic coast? Regulatory challenges of certifying integrated shrimp-mangrove production systems in Vietnam. J Rural Stud 28:631–639

Hall SJ, Delaporte A, Phillips MJ et al. (2011) Blue Frontiers: Managing the Environmental Costs of Aquaculture. The WorldFish Center, Penang

Halwart M, Gupta MV (2004) Culture of Fish in Rice Fields. Food and Agriculture Organization of the United Nations and the WorldFish Center, Penang

Halwart M, van Dam AA (eds) (2006) Integrated Irrigation and Aquaculture in West Africa: Concepts, Practices and Potential. Food and Agriculture Organization of the United Nations, Rome

Hanjra MA, Qureshi ME (2010) Global water crisis and future food security in an era of climate change. Food Policy 35:365–377

Hindar K, Fleming IA, McGinnity P et al. (2006) Genetic and ecological effects of salmon farming on wild salmon: modelling from experimental results. ICES J Mar Sci 63:1234–1247

Hunter MC, Smith RG, Schipanski ME et al. (2017) Agriculture in 2050: recalibrating targets for sustainable intensification. BioScience 67:386–391

INMED (2011) Aquaponics: Combating Food Insecurity, Protecting the Environment and Generating Income through Adaptive Agriculture. INMED Pamphlet, Jamaica

IPCC (2014) Climate Change 2014: Synthesis Report – Summary for Policymakers. Intergovernmental Panel on Climate Change, Valencia

Irving AD, Connell SD, Russell BD (2011) Restoring coastal plants to improve global carbon storage: reaping what we sow. PLoS ONE 6(3):e18311

Jackson A (2009) Fish in – fish out ratios explained. Aquac Eur 34 (3):5–10

Kapetsky JM, Aguilar-Manjarrez J, Jenness J (2013) A Global Assessment of Offshore Mariculture Potential from a Spatial Perspective. FAO Fisheries and Aquaculture Technical Paper No. 549, Rome

Kauffman JB, Arifanti VB, Trejo HH et al. (2017) The jumbo carbon footprint of a shrimp: carbon losses from mangrove deforestation. Front Ecol Environ 15:183–188

Kauffman JB, Heider C, Norfolk J et al. (2014) Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecol Appl 24:518–527

Klamt A-M, Schernewski G (2013) Climate change – a new opportunity for mussel farming in the southern Baltic? In: Schmidt-Thomé P, Klein J (eds), Climate Change Adaptation in Practice: From Strategy Development to Implementation. John Wiley & Sons Ltd, New Jersey, pp 171–184

Knutson TR, McBride JL, Chan J et al. (2010) Tropical cyclones and climate change. Nat Geosci 3:157–163

Kopp RE, DeConto RM, Bader DA et al. (2017) Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. Earth's Future 5:1217–1233

Kroeker KJ, Kordas RL, Crim R et al. (2013) Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob Change Biol 19:1884–1896

Kültz D (2015) Physiological mechanisms used by fish to cope with salinity stress. J Exp Biol 218:1907–1914

Kwiatkowski L, Bopp L, Aumount O et al. (2017) Emergent constraints on projections of declining primary production in the tropical oceans. Nat Clim Change 7:355–358

Lebel L, Tri NH, Saengnoree A et al. (2002) Industrial transformation and shrimp aquaculture in Thailand and Vietnam: pathways to ecological, social, and economic sustainability? Ambio 31:311–323

Liu B, Yu Z, Song X et al. (2006) The effect of acute salinity change on white spot syndrome (WSS) outbreaks in *Fenneropenaeus chinensis*. Aquaculture 253:163–170

Love DC, Fry JP, Genello L et al. (2014) An international survey of aquaponics practitioners. PLoS ONE 9(7):e102662

Love DC, Fry JP, Li X et al. (2015) Commercial aquaponics production and profitability: findings from an international survey. Aquaculture 435:67–74

Martinez-Porchas M, Martinez-Cordova LR (2012) World aquaculture: environmental impacts and troubleshooting alternatives. Sci World J 2012:389623

Mcleod E, Chmura GL, Bouillon S et al. (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front Ecol Environ 9:552–560

Miao W, Yuan X (2007) The carp farming industry in China – an overview. In: Leung PS, Lee C-S, O'Bryen PJ (eds), Species and

System Selection for Sustainable Aquaculture. Blackwell Publishing, Oxford, pp 373–388

Miller DD, Ota Y, Sumaila UR et al. (2018) Adaptation strategies to climate change in marine systems. Glob Change Biol 24:e1–e14

Mohanty RK, Verma HN, Brahmanand PS (2004) Performance evaluation of rice-fish integration system in rainfed medium land ecosystem. Aquaculture 230:125–135

Mungkung R, Phillips M, Castine S et al. (2014) Exploratory Analysis of Resource Demand and the Environmental Footprint of Future Aquaculture Development Using Life Cycle Assessment. WorldFish, Penang

Muñoz NJ, Farrell AP, Heath JW et al. (2015) Adaptive potential of a Pacific salmon challenged by climate change. Nat Clim Change 5:163–166

NACA (2012) Vulnerability and Adaptation to Climate Change for Improved Polyculture Farming Systems in the Mekong Delta, Viet Nam – Case Study Report. Network of Aquaculture Centres in Asia-Pacific, Bangkok

Naylor RL, Goldburg RJ, Primavera JH et al. (2000) Effect of aquaculture on world fish supplies. Nature 405:1017–1024

Naylor R, Hindar K, Fleming IA et al. (2005) Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. BioScience 55:427–437

Naylor RL, Williams SL, Strong DR (2001) Aquaculture – a gateway for exotic species. Science 294:1655–1656

Nearing MA, Pruski FF, O'Neal MR (2004) Expected climate change impacts on soil erosion rates: a review. J Soil Water Conserv 59:43–50

Nguyen AL, Dang VH, Bosma RH et al. (2014) Simulated impacts of climate change on current farming locations of striped catfish (*Pangasianodon hypophthalmus*; Sauvage) in the Mekong Delta, Vietnam. Ambio 43:1059–1068

Nhan DK, Phong LT, Verdegem MJC et al. (2007) Integrated freshwater aquaculture, crop and livestock production in the Mekong delta, Vietnam: determinants and the role of the pond. Agric Syst 94:445–458

Nicholls RJ, Wong PP, Burkett VR et al. (2007) Coastal systems and low-lying areas. In: Parry ML, Canziani OF, Palutikof JP et al. (eds) Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK, pp 315–356

Ottolenghi F, Silvestri C, Giordano P et al. (2004) Capture-based Aquaculture: the Fattening of Eels, Groupers, Tunas and Yellowtails. Food and Agriculture Organization of the United Nations, Rome

Pahlow M, van Oel PR, Mekonnen MM et al. (2015) Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production. Sci Total Environ 536:847–857

Panagos P, Ballabio C, Meusburger K et al. (2017) Towards estimates of future rainfall erosivity in Europe based on REDES and WorldClim datasets. J Hydrol 548:251–262

Pant J, Demaine H, Edwards P (2004) Assessment of the aquaculture subsystem in integrated agriculture-aquaculture systems in Northeast Thailand. Aquac Res 35:289–298

Park C-E, Jeong S-J, Joshi M et al. (2018) Keeping global warming within 1.5 °C constraints emergence of aridification. Nat Clim Change 8:70–74

Pendleton L, Donato DC, Murray BC et al. (2012) Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS ONE 7(9):e43542

Peperzak L (2003) Climate change and harmful algal blooms in the North Sea. Acta Oecologica 24:S139–S144

Primavera JH (2006) Overcoming the impacts of aquaculture on the coastal zone. Ocean Coast Manag 49:531–545

Primavera JH, Garcia LMB, Castaños MT et al. (eds) (2000) Mangrove-Friendly Aquaculture: Proceedings of the Workshop on Mangrove-Friendly Aquaculture. Organized by the SEAFDEC, Iloilo City, Philippines

Robb DHF, MacLeod M, Hasan MR et al. (2017) Greenhouse gas emissions from aquaculture: a life cycle assessment of three asian systems. FAO Fisheries and Aquaculture Technical Paper No. 609, Rome

Schmidhuber J, Tubiello FN (2007) Global food security under climate change. Proc Natl. Acad. Sci USA 104:19703–19708

Shelton C (2014) Climate Change Adaptation in Fisheries and Aquaculture – Compilation of Initial Examples. FAO Fisheries and Aquaculture Circulation No. 1088, Rome

Siikamäki J, Sanchirico JN, Jardine S et al. (2012) Blue Carbon: Global Options for Reducing Emissions from the Degradation and Development of Coastal Ecosystems. Resources for the Future, Washington DC

Simpson S (2011) The blue food revolution: making aquaculture a sustainable food source. Scientific American February:54–61

Soto D, Jara F, Moreno C (2001) Escaped salmon in the inner seas, southern Chile: facing ecological and social conflicts. Ecol Appl 11:1750–1762

Sreejariya P, Gallardo W, Dabbadie L (2011) The Role of Integrated Multi-Trophic Aquaculture (IMTA) in Climate Change Mitigation and Adaptation. Asian Institute of Technology, Bangkok

Sweet WV, Horton R, Kopp RE et al. (2017) Sea level rise. In: Wuebbles DJ, Fahey DW, Hibbard KA et al. (eds) Climate Science Special Report: Fourth National Climate Assessment. U. S. Global Change Research Program, Washington DC, pp 333–363

Tacon AGJ, Metian M (2008) Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. Aquaculture 285:146–158

Tacon AGJ, Hasan MR, Metian M (2011) Demand and Supply of Feed Ingredients for Farmed Fish and Crustaceans: Trends and Prospects. FAO Fisheries and Aquaculture Technical Paper No. 564, Rome

Torrissen O, Jones S, Asche F et al. (2013) Salmon lice – impact on wild salmonids and salmon aquaculture. J Fish Dis 36:171–194

Troell M, Joyce A, Chopin T et al. (2009) Ecological engineering in aquaculture – potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture 297:1–9

Turral H, Burke J, Faurés J-M (2011) Climate Change, Water and Food Security. Food and Agriculture Organization of the United Nations, Rome

UNEP (2014) The Importance of Mangroves to People: A Call to Action. UNEP World Conservation Monitoring Centre, Cambridge

United Nations (2017) World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Population Division, United Nations, New York, NY

Valiela I, Bowen JL, York JK (2001) Mangrove forests: one of the world's threatened major tropical environments. BioScience 51:807–815

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

Vitousek S, Barnard PL, Fletcher CH et al. (2017) Doubling of coastal flooding frequency within decades due to sea-level rise. Sci Rep 7:1399

Waite R, Beveridge M, Brummett R et al. (2014) Improving Productivity and Environmental Performance of Aquaculture. World Resources Institute, Washington DC

Wheeler T, von Braun J (2013) Climate change impacts on global food security. Science 341:508–513

Williamson P, Turley C (2012) Ocean acidification in a geoengineering context. Philos Transect R Soc A 370:4317–4342

Wisser D, Frolking S, Douglas EM et al. (2010) The significance of local water resources captured in small reservoirs for crop production – a global-scale analysis. J Hydrol 384:264–275

Woodward G, Perkins DM, Brown LE (2010) Climate change and freshwater ecosystems: impacts across multiple levels of organization. Philos Trans R Soc B 365:2093–2106

World Bank (2013) Fish to 2030: Prospects for Fisheries and Aquaculture. The World Bank, Washington DC

WWDR4 (2012) Managing Water under Uncertainty and Risk. The United Nations World Water Development Report 4. United Nations World Water Assessment Program, New York, NY

Xiao X, Agusti S, Lin F et al. (2017) Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. Sci Rep 7:46613