The Perspective of Climate Change on the Aquatic Environment and Fish Production

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Abstract

Climate change, a burning global issue, has had and will continue to impact our environment significantly. Over the years, natural and anthropogenic factors have affected climate leading to alterations in monsoon patterns, North Atlantic Oscillation El Nino/Southern Oscillation, and other changes. In the future, the overall carbon dioxide balance and the foreseen changes are likely to weaken the efficiency of carbon dioxide removal from the atmosphere, disturbing the aquatic environment and ecosystem. Changes in the aquatic environment directly affect the food chain, disturbing the abundance of marine and inland fishes, their recruitment, catch, etc. Global changes in the aquatic environment are likely to change the limits of marine protected areas, and low-lying island countries dependent on coastal economies. Disturbance in the aquatic environment will also affect the propagation of phytoplankton and other algae which could reduce the concentration of atmospheric oxygen. The autotrophic phytoplankton act as carbon dioxide sinks and account for nearly half of the total global photosynthesis. Their absence would have severe consequences as the aquatic food chain would get cracked. Looking at this foreseen situation faced by humans the chapter is attempted to present some insights due to climate change with severe consequences for the aquatic environment and fish production.

Keywords

Aquatic environment · Climate change · Fish production

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1 Introduction

Climate change refers to a persistent alteration of temperature and distinct weather patterns in a specific location or the planet as a whole. Climate, often confused with the weather, includes weather conditions exclusively averaged over a few decades for a particular place. On the other hand, the weather has temperature, atmospheric pressure, wind, humidity, precipitation, and cloud cover during the day. In simple words, the weather is a term that expresses the degree to which it may be cold or hot, high or low, gusty or calm, dry or muggy, rainy or snowy, with a clear or obscure sky.

Climate change, the consequence of burning fossil fuels, for example, oil, gas, and coal, is having a catastrophic effect on our environment. When burnt, the fossil fuels liberate carbon dioxide into the air, subsequently heating the earth. Climate change has not spared any form of life on earth, be it aquatic or terrestrial. According to the Intergovernmental Panel on Climate Change (IPCC), climate change can contribute to the global rise in sea level up to 1 m (Rahmstorf 2010) if greenhouse gas emissions keep escalating. Precision satellite altimeter data of 25-year time series suggests that the global mean sea level could rise 65 ± 12 cm by 2100 compared to 2005. This report is quite close to the one from IPCC's fifth Assessment Report (AR5) model projections (Nerem et al. 2018). There has been an upsurge in the pieces of evidence supporting rapid climate change. It is predicted that by the year 2100, the global temperatures will increase by 4 °C, with notable differences in precipitation patterns. Thus, in this situation, assessing the costs of biodiversity and its mitigation remains a daunting task for ecologists (Thuiller 2007).

Assimilation of incoming solar energy and reflected radiant energy are the consequences of greenhouse gases, for example, carbon dioxide, methane, etc. Changes in the concentrations of greenhouse and other atmospheric gases disturb the global radiation budget (Gribbin 1988), which results in an escalation of atmospheric temperature. A rise in atmospheric temperature by a few degrees can cause hydrologic changes that can disturb water's physical and chemical properties. Further, minor temperature changes can have a significant influence on climate (Roessig et al. 2004), leading to changes in the aquatic environment with alterations in aquatic life, namely fish, invertebrates, and plant species of marine and estuarine ecosystems (Kitaysky and Golubova 2000; Stevenson et al. 2002). Thus, with a relatively small temperature rise, there is a change in distribution and shifts in marine and inland fishes (Perry et al. 2005; reviewed by Myers et al. 2017).

With the expansion of industrialization, different detrimental compounds are being introduced into the atmosphere, resulting in intense environmental alterations. These environmental alterations have enabled the retention of radiant energy, ensuing in elevated atmospheric temperature that impacts climate. These climatic changes influence ecosystems, communities, and population structures (Walther et al. 2002). A scale of such changes has been observed in aquatic and terrestrial systems (Root et al. 2003; Parmesan and Yohe 2003; Perry et al. 2005). Other issues affected by global climate change include alteration in boundaries of marine protected areas and low-lying island countries dependent on coastal economies and diseases (Perry et al. 2005).

Carbon dioxide (CO_2), a greenhouse gas that accounts for climate change, is highly soluble in water. It results in the accumulation of more bicarbonate as a consequence of increased levels of atmospheric CO_2. Enhanced water temperatures, and acidification of aquatic water bodies, including oceans, have severely affected the aquatic environment (Roessig et al. 2004; Nikinmaa 2013) and even involved the distribution shifts in marine fishes (Perry et al. 2005). As a consequence of a rise in sea temperature, it is known that the distribution of exploited and non-exploited fish was affected as nearly two-thirds of species shifted in mean latitude or depth or both over 25 years (Perry et al. 2005). Alterations in inland aquatic ecosystems through a change in water quality and other pathways have also been predicted (Nikinmaa 2013; Chen et al. 2016). Expected climate change in the future is likely to harm inland as well as marine aquatic ecosystems through different pathways, along with alterations in water quality (Kitaysky and Golubova 2000; Winslow et al. 2003; Paukert et al. 2017). Thus, devastating effects can be well predicted for the aquatic ecosystems as the nature of interaction among different aquatic organisms can be altered due to an increase in water temperature and other factors (Roessig et al. 2004; Myers et al. 2017; Timoner et al. 2021; Whitfield 2021).

2 Factors Responsible for Climate Change

Several factors bring about climate change. Increased sea levels, construction of dams, scarcity of food, temperature variations, gaseous emissions, and increased rate of evaporation are some crucial factors responsible for climate change that is known to cause alteration in an aquatic environment. It is predicted that climate change would accelerate the melting of glaciers. The thermal expansion of seawater will raise the sea level by nearly half a meter by 2100, disturbing life in aquatic ecosystems to a great extent. This would seriously affect aquatic organisms as their existence may be threatened or extinct by the end of the century (Williamson and Guinder 2021). Manmade dams can alter the local climatic conditions and are already harming ecological niches by disturbing the native biodiversity, including the migration patterns and breeding of aquatic organisms (Null et al. 2013; Kirkland et al. 2021; O'Mara et al. 2021).

2.1 Water Regulation and Manmade Dams

It has been demonstrated that the Coldwater habitat for fish species has been reduced by water regulation, construction of dams, and land-use change with a variation in stream temperatures. Climate change has consequences on hydroclimatic conditions and impacts water temperatures downstream of the dams, affecting ecology as stream temperatures are sensitive to fluctuations. Thus, reservoir regulation affects stream temperatures and Coldwater habitat with climate change (Null et al. 2013). A recent study conducted at 30 dam sites across various environmental settings throughout Massachusetts (USA) has shown that most dams warmed temperatures downstream with variable magnitudes. It was observed that cool headwater streams having wide impoundments faced maximum warming. It was intriguing to note that 75% of the cold/cool water sites shifted to warmer thermal classes downstream, with the thermal effects of dams being most significant during the lower flow periods (Zaidel et al. 2021). A similar phenomenon has been predicted for Indian Coldwater fishes, as a variation in the pattern of the reproductive biology of golden mahseer from the lesser Himalayan region concerning regional climate change had consequences on breeding phenology (Joshi et al. 2018).

2.2 Climate Change and Air Quality

Deforestation, considered responsible for climate change, seriously affects the quality of air that we breath. An essential but usually ignored carbon dioxide consumer group is the autotrophic phytoplankton that acts as carbon dioxide sinks. Moreover, the autotrophic phytoplankton accounts for nearly half of global photosynthesis. However, terrestrial plants have always gathered attention (Falkowski 2012). Alteration in an abundance of phytoplankton will affect the overall carbon dioxide balance via the oceanic carbon cycle. The foreseen changes would diminish carbon dioxide removal from the atmosphere (Cermeno et al. 2008). Notably, there has been a global decrease in oceanic phytoplankton (Boyce et al. 2010) which is alarming.

2.3 Ocean Acidification

Ocean acidification, a result of rising atmospheric carbon dioxide (CO_2), is a consequence of burning human fossil fuels. Atmospheric CO_2 reduces ocean pH and causes a comprehensive shift in carbonate content, thereby altering the water chemistry. The process of ocean acidification is well documented, and it is predicted that the rate will accelerate over this century if forthcoming CO_2 emissions are not curbed. As a result of acidification, chemical speciation and biogeochemical cycles of many elements and compounds in the seawater can be altered (Doney et al. 2009). One of the consequences of acidification is the reduced calcium carbonate saturation states, which influences shell formation in marine organisms from plankton to benthic molluscs, echinoderms, and corals. However, ocean acidification may increase carbon fixation rates in some photosynthetic organisms (reviewed by Doney et al. 2009).

2.4 Solar Forcing

Solar forcing or the changes in solar radiation in a climate model is also known to affect the aquatic environment. Solar forcing can shift towards the Arctic Oscillation/ North Atlantic Oscillation during periods of reduced solar forcing. Reduction in solar irradiance leads to colder temperatures over the continents in the Northern Hemisphere, especially during winter (1–2 °C), a fact that is in agreement with historical records and proxy data for surface temperatures (Shindell et al. 2001). It is predicted that by 2100, global ocean temperatures will increase by 1–4 °C. The increased temperatures will affect the stress physiology of fish as they are most vulnerable to global warming (Alfonso et al. 2021). The enhanced temperature may alter the capacity of fishes to cope with other stressors, compromising their fitness. In addition, rapid temperature increases are known to induce acute stress responses in fishes and might be of ecological relevance in particular situations. Fishes exposed to high temperatures cause stress that triggers the release of catecholamines and cortisol. Elevated cortisol responses due to an acute rise in temperature have been reported in several fishes, with a few exceptions (reviewed by Alfonso et al. 2021).

2.5 Anthropogenic and Natural Causes

Anthropogenic activities like the expansion of cities, industrialization, deforestation, burning of wood, and agricultural activities contribute to greenhouse gases. For instance, livestock produces methane during enteric fermentation, while an enormous amount of nitrous oxide is generated during the manufacture of chemical fertilizers. Anthropogenic interventions have led to the increase in greenhouse gases, namely carbon dioxide, methane, nitrous oxide, and halogenated compounds, for example, CFCs and SF6 are significant contributors that accumulate in the atmosphere and trap the sun's heat reflected from the earth leading to the phenomenon of the greenhouse effect (Wallington et al. 2009; Kweku et al. 2017).

Several studies on historical records on climate change show that anthropogenic and natural causes affected global greenhouse warming over the twentieth century, with an accelerated upsurge in aerosol sulfate emissions which started around 1950 (Crowley 2000; Jones and Mann 2004; Stern and Kaufmann 2014; Hegerl et al. 2019). Based on modeling and attribution studies, it is known that aerosol forcing influences regional temperatures, leading to continuing alterations in monsoon patterns besides Atlantic variability. These historical changes in atmospheric conditions are said to be responsible for long-term climate variability. For example, the North Atlantic Oscillation (Hegerl et al. 2019) is known to disturb wind speed and direction, besides alterations in air temperature and rainfall. North Atlantic Oscillation is known to affect fishery resources and fishery yields by aggravating the abundance of target species, their recruitment, catchability, and body condition with cumulative and synergistic action (Báez et al. 2021). Some of the consequences that can be foreseen include distribution and shifts in marine and inland fishes (Perry et al. 2005).

2.6 Temperature

In Black Sea trout (*Salmo trutta* labrax Pallas, 1814), an acute increase in temperature can trigger secondary stress responses marked by elevated glucose and lactate levels because of critical thermal challenges. Temperature fluctuations may also alter blood osmolality besides hematological variables. Besides having an inhibitory effect on the fish immune system, acute thermal stress can also affect total protein and serum ion concentrations. It has been observed that short-term acute thermal exposure can also result in serum ionic imbalance in trout, with the restoration of homeostasis (Bard and Kieffer 2019; Dengiz Balta et al. 2017). Further, thermal stress can alter the levels of heat shock protein (HSPs) at the cellular level by affecting the endocrine stress system. For instance, in red blood cells of rainbow trout *Oncorhynchus mykiss* (Walbaum 1792), the adrenergic system can enhance the response of HSP, while cortisol inhibited heat stress-induced levels of HSPs (reviewed in Alfonso et al. 2021). Chronic exposure to elevated temperature can lead to severe consequences for the resting stress physiology of fish because of alteration in the brain’s noradrenergic and dopaminergic systems. Moreover, a warmer climate can also alter the stress-coping capacities of fish.

3 Climate Change and Aquatic Environment

The quality of water in an aquatic environment can have a remarkable change in the aquatic habitat. Gaseous emissions in the form of CO_2, SO_2, and oxides of nitrogen (NOX) can alter the precipitation chemistry of water. An increase in the concentration of SO_2 results in more sulfate ions that enter water bodies, reducing their pH. Acidification and increased water temperatures directly affect dissolved organic carbon (Evans et al. 2005). It is known that pH and dissolved organic carbon impact the bioavailability of mercury at the bottom of the aquatic food chain (Adams et al. 2009; Dittman and Driscoll 2009). Bioaccumulated mercury in aquatic food chains can attain maximum concentrations in edible tissues of fish living in freshwater and marine environments. Mercury absorbed from the diet gets distributed to all the tissues in the body. Thus, consuming such fish can introduce mercury in humans, which can easily cross the blood-brain and placental barriers resulting in several neurological manifestations (Fitzgerald and Lamborg 2014; Clarkson 1993; Amap/UNEP 2015).

Alteration in precipitation patterns and increased air temperature can change stream and river discharge patterns (Clow 2010; Leppi et al. 2012). Rising air temperatures in ice- or snow-covered regions will speed up snow melting, alter the hydrological system by increasing nearby streams’ flow, and create a water deficit late in the season. These late-season shortages leave less water in the channel to be warmed during the hottest months of the year. Though concentrations of chemicals are likely to be diluted during high flows, the total pollutant load may increase (Grigas et al. 2015). Chemical concentrations and water temperatures will increase during low flows, but the whole load may also decrease. For instance, in the

Mississippi River Basin, runoff of agricultural nutrients (e.g., nitrogen and phosphorus) and sediment would have relatively higher concentrations but low total loads. In some extreme conditions, high flow can cause high concentrations of these agricultural pollutants (Reba et al. 2013). A similar flow of chemical concentration/load pattern has been witnessed in urbanized watersheds (e.g., Grigas et al. 2015).

Similarly, rock weathering and solute transport components are influenced either directly or indirectly by the local climate. Local hydrology, directly linked to the environment, governs the subsurface flow of oxygen and water and the surface and subsurface transport of weathering products. Further, both temperature and hydrology strongly influence watershed geochemical reaction rates and, as such, define the resultant water chemistry in waterbodies draining those watersheds. Significant changes in climatic conditions, such as thermal and hydrological regimes within mineralized areas, can change watershed chemistry (Rogora et al. 2003).

Several studies have documented increases in rock weathering solutes (e.g., dissolved sulfate) over the last several decades attributed to increases in climatic warming (Mast et al. 2011). A recent study has documented that increased concentrations of dissolved metals are known to be the products of pyrite weathering that are toxic to freshwater fishes (e.g., Zn, Cu, Cd; Todd et al. 2012). This study concluded that upsurges in concentrations of instream toxic metal were likely attributable to several climate-influenced factors, including increased rock weathering, new subsurface flow, weathering pathways resulting from loss of frozen surface ground, and a decreasing groundwater table (Todd et al. 2012). Notably, if water chemistry changes, the downstream water quality worsens and may increase toxicity thresholds that directly affect fisheries.

Global climate change is also predicted to change air temperature, precipitation, and emissions of CO_2, SO_2, and NOX. Other effect leads to increased water temperatures, reduced dissolved oxygen concentration, altered water chemistry, and chemical load. One of the costs of climate change is the geographically atypical warming of oceans. Changes in temperature and salinity due to global warming can mutually reduce the density of the ocean surface, intensify vertical stratification, and alter surface mixing. Moreover, evidence suggests that inland waters are warming, as well as influencing river runoff. An increase in vertical stratification and water column stability in the oceans and lakes can reduce accessibility to nutrients in the euphotic zones affecting primary and secondary production (Barange and Perry 2009).

Climate change has also been associated with upwelling. Upwelling is a phenomenon in which deep coldwater rises towards the surface. Winds that blow across the ocean surface push the water away, resulting in the rising of underneath water to the surface thus, replacing the water moved away. Climate change can alter upwelling, as evidence shows that the seasonality of upwelling may be affected due to climate change. However, to understand coastal upwelling, the present climate models are inadequately developed and require refinement to predict rising sea levels. Rising sea levels will remain a severe concern for low-lying coastal areas, for example, small-island regions, coastal Americas of the Atlantic and Gulf of Mexico, the Mediterranean, the Baltic, and Asian mega deltas (Barange and Perry 2009).

It is well known that the phenomenon of ocean acidification has been reducing the pH of the water in the marine environment. It is predicted that a further reduction in pH will have severe consequences for shell-bearing organisms, tropical coral reefs, and coldwater corals. Climate change will affect inland ecosystems resulting in altered land use, including variations in sediment loads, water flows, and physico-chemical changes. These changes will impact community composition, production, and seasonality in plankton and fish populations, putting additional pressure on inland fish production (Barange and Perry 2009).

4 Climate Change and Plankton

Planktons are tiny organisms that can affect climate in several ways. They absorb and scatter light, warm the ocean's top layers, and produce volatile organic compounds, such as dimethyl sulfide, which supports the formation of clouds. Planktons play an essential role in moving carbon around the oceans, on a scale large enough to affect carbon dioxide levels in the atmosphere (Falkowski 1994).

It can be foreseen that the climate will get warmer in the next century due to an increase in greenhouse gases, and so will the oceans. Warm climatic conditions would deplete oxygen in the water and result in a reduction of phytoplankton. Since 1950, there has been a spectacular reduction in phytoplankton due to the gradual warming of the oceans. It is known that phytoplankton thrives better in cooler waters. Therefore, they migrate to cooler areas of the sea when other parts turn too warm. Oceanographers have tracked environmental changes like temperature and salinity to estimate the migration of phytoplankton over the next century. It is predicted that phytoplankton along the North Atlantic coast will migrate towards cooler waters off the coast of Greenland, reducing the source of food for fish and other aquatic organisms.

Phytoplanktons play an integral role in moderating the earth's climate as they absorb CO_2 emissions. Phytoplanktons absorb CO_2 as plants do, and when dead, they sink to the bottom of the ocean, locking the carbon for several millennia. Phytoplankton account for half of the global photosynthesis preventing global warming to a great extent (Huertas et al. 2011).

Significant and globally consistent shifts have been detected in species phenology, range extension, and community composition in marine ecosystems (Beaugrand et al. 2003). The shift in plankton communities towards the poles indicates ocean warming and its impact on marine ecosystems. Global shifts in zooplankton populations can affect marine life that feeds on plankton, especially fish (Jonkers et al. 2019). On comparing pre-industrial and modern-day zooplankton samples, it has been assessed that the average community had shifted 602 km towards the poles from the pre-industrial era to date. However, the degree of displacement ranged from 45 to 2557 km, depending on the degree of change in sea surface temperature. In the northern hemisphere, it was found that plankton communities had shifted northwards in response to ocean warming. Some species that feed on zooplankton would migrate to cooler waters, while others may not do so and thus eventually perish.

5 Climate Change and Benthic Community

Information about benthic variability about climate change and other effects is meagerly available. Efforts are on to unravel more evidence from time-series observations. Climate change may modify population dynamics over time and space, phenology, and geographical distribution of communities and species (Dulvy et al. 2008; Birchenough et al. 2011). Under such conditions, several species would lose their habitat and become extinct in the aftermath of biogeochemical changes, ecosystem functioning, and biodiversity. Habitat loss and extinction can be expected over time, with aftermaths of biogeochemical changes, ecosystem functioning, and biodiversity.

6 Climate Change and Fish Production

Several effects of climate change have been observed on the ecosystem and fish production. In recent decades, the global primary production of the oceans has shown a trivial decrease. In contrast, a slight upsurge in global primary production is expected over this century, however, with enormous regional differences (Barange and Perry 2009). There would be reduced ice cover, warmer-water temperatures, longer seasons due to increased algal abundance, and productivity in high-latitude/altitude lakes (Mcclanahan and Cinner 2012). However, diminished algal mass and reduction in productivity are also predicted primarily due to the reduced resupply of nutrients in some deep tropical lakes. It is expected that the intensification of hydrological cycles may substantially influence the limnological progressions. It would affect the productivity of all forms of aquatic life because of augmented runoff, discharge rates, flooding areas, and water levels during the dry season (Mcclanahan and Cinner 2012).

Climate change is said to direct most terrestrial and marine species near the poles, intensifying the propagation of warmer-water species and shrinking the ones in colder water. The most rapid switches are projected to occur in fish communities in the oceans, including those that would migrate in response to surface warming, resulting in a surge in abundance towards the poles. In contrast, a decline in populations near the equator will be inevitable.

An increase in temperature and light intensification would result in differential responses between plankton components suggesting an alteration in the environment of marine and freshwater fishes due to predator-prey mismatch (Barange and Perry 2009). Although there is a limited conformation supporting upsurge in outbreaks of disease related to global warming, however, dissemination of pathogens to higher latitudes has been observed, which might lead to some emerging diseases.

In a rapid timescale, i.e., within a few years, rising temperatures will negatively impact fish physiology resulting in considerable limitations for aquaculture, and alteration in the distribution of species, besides possible changes in abundance as recruitment processes will be afflicted. The timings of important events like life history would diminish, particularly affecting short-lived species like plankton, squid, and small pelagic fishes. During intermediate time scales ranging from a few years to a decade, the recruitment success would be altered due to temperature-mediated physiological stresses and changes in phenology impacting the abundances of several marine and inland fish populations. However, the predicted impacts at multi-decadal or long-time scales would depend upon changes in net primary production in the oceans and their transfer to higher trophic levels (Barange and Perry 2009). A global model has been predicted for the 2050s considering different life stages, timeframes, and dispersal scenarios to unravel the thermal performances of *Salmo trutta* and *Salmo salar*. It has been demonstrated that thermal performances of varying life stages would fluctuate for specific periods. The thermal performances and model predictions suggest declines in habitat area and poleward shifts. The fish would disperse to find suitable habitats to mitigate the warming effects. However, dams may restrict their movement to sites linked to high performance (Kärcher et al. 2021). Similarly, concerns have been raised about the Atlantic salmon, which faces the challenges of reduced marine survival in a rapidly changing environment, as a consequence of climate change (Thorstad et al. 2021).

7 Impact on Inland Ecosystem

Climate change is causing alteration in the composition of species assemblages, abundance, biomass and distribution, fish yields, and the efficiency of fishing methods and gears. Inland fisheries have a significant contribution to meeting the food and livelihood demands of the fishing community. Unfortunately, diverse anthropogenic interventions have resulted in climate change affecting both fish and fishing communities. Injudicious use of water, overfishing, the introduction of exotic species, pollution, habitat degradation, and the rising human population have dented inland fisheries globally. Therefore, climate change will lead to changes in freshwater habitats and the fish assemblages they support. However, a few of these effects may benefit inland fisheries, especially those based on native fish populations (Harrod et al. 2019).

Freshwater ecosystems have a reasonably low buffering capacity and are relatively sensitive to climate-related variability. There can be a range of physiological and ecological impacts on fish and freshwater ecosystems supporting inland fisheries related to water temperature, water availability and flow, and other environmental disturbances. Climate change is expected to impact inland fisheries due to cumulative deviations in water temperature, nutrient levels, and precipitation patterns. For example, in the Ganga River system, most fish breed during the monsoon because of their dependence on seasonal floods. During the breeding months, a fall in precipitation may alter the required flow of turbidity essential for breeding the Indian major carp (IMC). A shift in rainfall pattern during the breeding season is responsible for the difficulties encountered in breeding and consequent recruitment of the IMCs juveniles in the river.

Impacts of direct and indirect climate change may lead to considerable shifts in species compositions. However, overall productivity may be sustained due to the high diversity and resilience of tropical systems and several invasive fish species. Climate change has continued to have a marked global impact on freshwater ecosystems, fish, and other aquatic taxa, besides providing goods and services, including fisheries (Myers et al. 2017). Almost all biological and chemical processes in freshwater ecosystems are influenced by temperature. Critical chemical transformations, dissolved oxygen concentrations, degradation, evaporation, the rate of biochemical processes within the aquatic organisms, disease risk, parasite transmissions, and the trophic interactions between consumers and their prey are some effects that are influenced by temperature (Miller et al. 2014). There would be harmful effects at longer time scales on Coldwater fish species compared with the ones inhabiting the warm water, which would be advantageous. The predicted response for cool water species would be beneficial in the northern parts but negatively affected in the southern parts of their range (reviewed by Barange and Perry 2009).

8 Impact on Marine Ecosystem

Climate change will have a marked effect on important marine organisms such as zooplankton constituting the base of the marine food chain, and calciferous organisms like shrimps, oysters, corals, and others. A rise in sea temperature is a significant reason for coral bleaching and reef ecosystem damage (Barange and Perry 2009). In 1997–1998 there was a mass bleaching event of corals worldwide with massive mortality, which overlapped with a large El Nino event, instantly switching over to a strong La Nina. Catastrophic bleaching with colossal mortality of about 95% was recorded from shallow and sometimes deep-water corals (Wilkinson 1998). It is predicted that carbon dioxide, a contributing factor to ocean acidification, could impair several ecosystems due to the elimination of several coral reefs. Mangroves and salt marshes are essential for maintaining wild fish stocks, and the source of seed for aquaculture would be lost. The marine food web may disrupt the food chain in the transformed marine ecosystem, eventually affecting marine fisheries and hamper distribution, productivity, and species composition of global fish production. The complex and interrelated impacts on oceans, estuaries, and seagrass beds provide habitats and nursery areas for fish that can shrink and eventually be lost. It is estimated that by 2100, the global fish catch from the oceans is expected to decline dramatically in global biomass and catches over the twenty-first century.

Diverse models predicting the effect of climate change suggest that by 2050 the potential of global fish catch may fluctuate by less than 10% depending on the trajectory of greenhouse gas emissions with significant geographical variability. It is predicted that reductions in marine and terrestrial production in almost 85% of coastal countries are anticipated with a wide variation in their nationwide adaptability. The distribution of zooplankton has transformed due to climate change, leading to a decline in fish production (Birchenough et al. 2011). The cool copepod assemblages have moved towards the north due to the warming of the oceans. The waters get warmer and are replaced by warm water copepod assemblages having lower biomass than other small species. In the North Sea, Atlantic cod spawn in spring, and their larvae feed on large copepods. Climate change has shifted copepod biomass in the North Sea. The unavailability of large copepods has resulted in high mortality rates and an alarming drop in the recruitment of these fish (Beaugrand et al. 2003; Richardson 2008).

Pelagic fish stocks have a unique spatial and temporal distribution pattern associated with their bioclimatic niche. Shifts in primary and secondary production have consequences on the distribution range, migratory habits, and stock size of many marine fish species due to climate change (Brander 2010). Reviewing the published data on North Atlantic fish species representing varied biogeographic affinities, habitats, and body size supports the hypothesis that global warming results in the shift, abundance, and distribution of different fish species (Rijnsdorp et al. 2009). Changes in migration patterns have been observed due to changes in zooplankton productivity due to climate change. Climate change has affected the distribution and expansion of several fish species. The distribution of Lusitanian species like horse mackerel, sprat, and anchovy has augmented in recent decades, particularly in the Northern limit of their distribution areas, while Borealis like cod and plaice have decreased at the southern boundaries. Still, cod has increased in the northern limit. So far, the existing pieces of evidence suggest that climate-related changes can alter the process of recruitment as a result of higher survival in the pelagic egg or larval stage due to variations in the nursery habitats (Rijnsdorp et al. 2009).

Some fish stocks act as biological indicators of extreme climate-induced fluctuations that can be significantly affected. The reproductive success, population dynamics, migration patterns, and interactions between specific fish populations such as straddling pelagic stocks like herring, mackerel, capelin, blue whiting, sprat, anchovy, and sardine can show a most crucial shift. The most noticeable effect of climate change will be a poleward expansion (Perry et al. 2005).

A shift away from shallow coastal waters and semi-enclosed areas is expected into deeper, cooler waters due to rising temperatures. Mostly, fish tend to live near their tolerance limits comprising a range of factors. Therefore, an increase in temperature and acidity reduced dissolved oxygen, and changes in salinity may have deleterious effects on their populations (Lehodey et al. 2006; Brander 2010).

In addition to the change in species distribution, invasive species, and extinction, the body size of fish might be reduced and lower the impact of fish stock recruitment when sea temperatures are elevated (Barange and Perry 2009). The potential for significant change in species abundance and composition could affect the whole ecosystem and the fisheries that rely on it. Some important marine ecosystems such as mangroves, seagrass, and coral reefs are under tremendous stress due to habitat destruction by human interference, pollution, etc. Climate change may add more stress and ultimately bring about structural and behavioral change in the ecosystem (Ficke et al. 2007; Barange and Perry 2009; Brander 2010).

9 Impact on Aquaculture

Climate change, a threat to global food production, can damage the quality and quantity of fish production. Global fish production has progressed continuously, reaching 46% of the estimated figures. Global fish production is expected to increase from 46% to 53% in 2030. However, the changing climate poses a challenge for the sector's fast, sustainable growth to meet the food requirements of the rapidly growing human population. Aquaculture, the fastest-growing global food-producing sector, has also been affected by climate change. The sector seems to be at risk because the predicted effects of climate change are alarming (reviewed by Maulu et al. 2021). The impact of climate change on aquaculture has been extensively reviewed (Maulu et al. 2021). Most of the studies in climate change have established adverse effects, overlooking the positive ones. Climate change, directly and indirectly, affects aquaculture production (Handisyde et al. 2006; De Silva and Soto 2009). The direct effects influence the physical and physiology of finfish and shellfish stocks in production systems. At the same time, indirect may alter the primary and secondary productivity and structure of the ecosystems, input supplies, and services needed by fishers and aquaculture producers. Global climate has significantly affected fish growth vulnerability to diseases, time of spawning, and mortality at certain stages of the life cycle with economic impact and implications for the cultural process (Maulu et al. 2021).

Bivalve culture is a relatively attractive method of producing a high-quality, healthy, and sustainable protein source for the expanding human population and constitutes a significant proportion of global mariculture (Stewart-Sinclair et al. 2020). Climate change resulting in coastal water acidification could have a severe impact on the production of bivalves. It has been advocated that global warming can also be advantageous for aquaculture as it may promote larval settlement. Attachment of early-stage bivalves may result in better growth rates of some farmed species (Bell et al. 2013). However, the acidification of the marine environment and the impact thereof on marine finfish are still unclear. Fish embryos and larvae being delicate as compared with juveniles and adults would be harmed the most, due to alteration in growth rate as a consequence of acidification of the aquatic environment (Heuer and Grosell 2014). Life-threatening weather happenings may record an upsurge in the frequency of physiological impacts on metabolism because of the variations in salinity and temperature (Pörtner et al. 2014). Such occasions may result in escaping of fish from aquaculture facilities besides the impairment of the infrastructure. Elevated temperatures, salinities, and lack of rain because of El Nino in 2015–2016 might have caused the triggering of algal blooms in the fjords of Southern Chile, with an estimated loss of more than 12% in Chilean salmon production (León-Muñoz et al. 2018). Climate change can also indirectly impact the aquatic ecosystem, for example, it may alter the prevalence of fish diseases and the production of seeds for aquaculture. Further, an indirect consequence of climate change would result in inadequate availability of fishmeal, fish oil, and “trash” fish that would also affect feed production and in turn aquaculture (Brander 2010; Merino et al. 2012).

Prevalence and occurrence of diseases in fish are likely as warm water pathogens may dominate. For example, *Vibrio* species grow preferentially in warm waters (>15 °C) and at low salinity (<25 ppm); therefore, vibriosis may be affected by climate change. The consequences of climate change are predicted to be more on tropical marine ecosystems (Pörtner et al. 2014; Brumfield et al. 2021). About 80% of the 26 million tonnes of marine food fish produced in 2013 were raised in Asia. Climate change may impact food security by the middle of the twenty-first century, with South Asia as the most severely affected region. Exposure and sensitivity to changing climate would make Bangladesh, China, Indonesia, Philippines, and Vietnam highly vulnerable (Handisyde et al. 2006) besides Ecuador, Egypt, Norway, and Chile. A recent reconsideration of the elevated rates of sea level (DeConto and Pollard 2016) suggests that unabated GHG emissions would result in a contribution of an extra 1 m of rising by 2100 from the Antarctic alone, which would significantly increase the impacts on the mariculture in highly vulnerable countries. Therefore, poor planning and bad management in aquaculture could enhance the vulnerability of coastal communities to climate change.

10 Adaptations and Their Implications

Adaptation is the tuning of natural or human systems in response to an actual or an expected change. Effects that can moderate damage or exploit beneficial opportunities are essential as climatic stimuli lead to adaptation. Adaptation can be achieved by reducing risks and vulnerabilities, identifying opportunities, and capacity building at all geographical and social scales to cope with current and expected impacts. Some of these measures may help natural systems adapt, but the focus is on humans rather than natural adaptation.

Some broad adaptation strategies that can be kept going in the face of adversity with relevance to fisheries and aquaculture systems are:

- Monitoring, forecasting, early warning data systems, and adaptation could be helpful in generating as well as sharing information about climate change.
- Projections and impact assessments of regional and local climate may be investigated for finding solutions.
- Integration of ways to adapt to climate change in decision-making, policies and procedures,
- Sustaining and augmenting the flexibility of natural and human systems circumventing obstructions in adaptation.
- Responding firmly to societal inequality and dissemination of the effects due to climate change.

- Implementation of green taxes or trading systems as adaptive measures to evade undesirable effects of climate change.

The Food and Agriculture Organization (FAO) advocates the control and management of fisheries to uphold healthy and productive ecosystems (Cochrane et al. 2009) that ensures the upkeep of structure, practices, roles, and interfaces between the components of the ecosystem strategically including and maintaining biodiversity. In some cases, for example in coastal environments and ecosystems, restoration of the habitat may be essential as a part of an ecosystem approach (Koehn et al. 2020). Adaptive actions may assist in the conservation of climate-induced changes, particularly in species composition. Therefore, management requirements may be enforced to adjust and respond to climate-induced changes such as changes in distribution, species composition, or productivity (Cochrane et al. 2009). The ecosystem approach to aquaculture offers the opportunity to consider climate change in the sector's planning and the refinement of management practices to effectively address climate inconsistency and drifts at scales ranging from individual to farm or a selected area under management. Several studies have identified possible adaptation strategies for mangrove systems and the people that use them. These include creating awareness of the importance of such systems among local communities and leaders, identifying critical areas, and minimizing stress unrelated to climate. Other issues that require attention are maintaining ecosystem connectivity, coastal planning that facilitates emergency retreats to inland areas, developing alternative livelihoods, and restoring coastal ecosystems. Experience suggests that it is necessary to integrate adaptation to climate change with the broader policy agenda.

11 Conclusion

Empirical evidence reveals that the warming up of the ocean affects the dissemination and periodic patterns of invertebrates, fish, and mammals. Such tendencies can continue in the future and lead to significant changes in the ecosystems. Threats due to climate change increase the collective impacts of other anthropogenic activities like over-exploitation, habitat degradation, pollution, eutrophication, and the introduction of species. The phenomenon is more prominent in the seas and oceans, which severely affects fisheries and aquaculture, as shown by several studies. Global warming could rapidly dry the water resources and even increase the salinity of groundwater, which will be detrimental to freshwater fisheries, aquaculture, and agriculture.

Moreover, such water would limit industrial and domestic usage. Studies on climate change suggest that 60% of coral reefs could be lost by 2030 and that increased acidification of oceans from higher levels of atmospheric carbon dioxide may be a contributing factor. Increasing temperature can also alter the physiological functions (thermal tolerance, growth, metabolism, food consumption, reproductive success, etc.) of the fish body to maintain homeostasis with the environment.

Adverse impacts of climate change are also putting enormous stresses on the lives and livelihoods of the people engaged in fisheries. It is foreseen that changes in intensity and seasonality of climate patterns would have serious consequences on fisheries. For instance, maritime territories extending 200 nautical miles from a country's coastline are exclusive economic zones (EEZs) with sovereign rights over natural resources. Impacts of climate change on fisheries potential of maritime territories are expected to be $<$10% between 2005 and 2050 for most EEZs, with an overall increase in production at mid to high latitudes and a decrease at low latitudes (Westerveld 2020). Therefore, managing existing fisheries and utilizing best management practices should counterbalance negating impacts of climate change on the potential of fisheries under an ecosystem-based approach. It is evident from the information that changes due to global warming will potentially have both favorable and unfavorable impacts on aquaculture. However, data indicate that adverse changes are likely to outweigh favorable ones, particularly in developing countries where adaptive capacity is the weakest. Adaptation to climate change must be undertaken within the multifaceted context, and any additional measures or actions taken in response to climate change should be a complement. Communities could help adapt to climate change by developing policies and programs to improve the resilience of natural resources through assessments of risk and vulnerability by increasing awareness of the impacts of climate change and by strengthening key institutions that would help the communities' adaptation. In this context, adopting climate resilience as an adaptation strategy will help meet the livelihood security of stakeholders associated with fisheries and aquaculture. The ecosystem approach to aquaculture offers the opportunity to consider climate change in the sector's planning and the development of management measures. Social and economic aspects and resource productivity need to be adapted for the management of fisheries to mitigate climate change. Moreover, ecological and human well-being are also warranted for the sustainability of aquatic resources. Advanced techniques and protocols need to be implemented for combating the changing climatic conditions.

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