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Solutions to blue carbon emissions: Shrimp cultivation, mangrove deforestation and climate change in coastal Bangladesh

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ABSTRACT

In Bangladesh, export-oriented shrimp farming is one of the most important sectors of the national economy. However, shrimp farming in coastal Bangladesh has devastating effects on mangrove forests. Mangroves are the most carbon-rich forests in the tropics, and blue carbon (i.e., carbon in coastal and marine ecosystems) emissions from mangrove deforestation due to shrimp cultivation are accumulating. These anthropogenic carbon emissions are the dominant cause of climate change, which in turn affect shrimp cultivation. Some adaptation strategies including Integrated Multi-Trophic Aquaculture (IMTA), mangrove restoration, and Reducing Emissions from Deforestation and forest Degradation (REDD+) could help to reduce blue carbon emissions. Translocation of shrimp culture from mangroves to open-water IMTA and restoration of habitats could reduce blue carbon emissions, which in turn would increase blue carbon sequestration. Mangrove restoration by the REDD+ program also has the potential to conserve mangroves for resilience to climate change. However, institutional support is needed to implement the proposed adaptation strategies.

1. Introduction

Bangladesh is one of the world's leading aquaculture producing countries with a production of 2.06 million tons in 2014–2015[1] [1]. Globally, Bangladesh is ranked 6th in aquaculture production after China, Indonesia, India, Vietnam, and the Philippines [2]. Bangladesh is one of the most suitable countries in the world for coastal aquaculture because of its favorable biophysical resources and agro-climatic conditions [3]. The coastal aquaculture sector is dominated by tiger shrimp (*Penaeus monodon*) farming. Over three-quarters of shrimp farms are located in southwest Bangladesh with the remainder in the southeast. In 2014–2015, total annual shrimp production in Bangladesh was estimated at 75,274 t from 216,468 ha area, with an average annual productivity of 348 kg/ha [1]. Shrimp culture has diversified livelihood opportunities for the coastal poor, with over two million people involved in shrimp farming, marketing, processing, and exporting [4].

Shrimp farming is currently one of the most important sectors of the national economy. The sector has become a multimillion dollar industry in Bangladesh due to huge demand for shrimp in global markets, particularly the European Union (EU) and the United States of America (USA). In 2014–2015, Bangladesh exported 44,278 t of prawn and shrimp valued at US$506 million, of which US$364 million (72%) was shrimp [1]. As a whole, the sector is the 2nd largest export industry after readymade garments. Overall, shrimp production plays an important role in export earnings, food production, diversifying livelihoods, and income for farming households and associated groups [3].

Despite economic benefits, shrimp farming in coastal Bangladesh has devastating effects on mangroves [5–7]. Globally, shrimp farming has been under intense criticism because of its socioeconomic and environmental impacts [8–10]. During the 1980s and 1990s, the rapid growth of shrimp farming caused widespread destruction of mangroves in a number of countries, including Bangladesh, Brazil, China, India, Indonesia, Malaysia, Mexico, Myanmar, Sri Lanka, the Philippines, Thailand, and Vietnam [11,12]. However, mangroves are the most carbon-rich forests in the tropics and blue carbon emissions[2] have been seriously augmented due to devastating effects on mangroves [13–16]. Carbon emissions with other greenhouse gases (CH_4, N_2O) are likely to have been the dominant cause of climate change [17]. It is, therefore, crucial to reduce blue carbon emissions from mangrove deforestation to tackle anthropogenic[3] climate change.

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[1] Bangladesh fiscal year: 1 July – 30 June.
[2] Emissions refer to the release of carbon into the atmosphere over a specified area and period of time.
[3] Anthropogenic climate change refers to the production of greenhouse gases emitted by human activity.

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Preventing mangrove loss and conserving mangrove forests can help to reduce blue carbon emissions for climate change mitigation [14,15,18]. The aim of this paper is to highlight key issues in reducing blue carbon emissions from mangrove deforestation due to shrimp cultivation in coastal Bangladesh. The conversion of mangrove forests into shrimp farms and the impacts of climate change on shrimp culture, mangrove fisheries, and coastal communities are also discussed. Finally, some adaptation strategies are proposed to reduce blue carbon emissions for resilience to climate change.

2. Shrimp cultivation and mangrove deforestation

2.1. The blue revolution of shrimp cultivation

As part of agricultural development in coastal Bangladesh, shrimp farming was initiated in the 1970s and began to expand rapidly in the 1980s [19]. During the 1990s, the rapid development of shrimp farming has been likened to the blue revolution, which is an approach to food production and economic growth [3]. Shrimp culture has developed extensively in coastal Bangladesh over the last three decades. Overall, shrimp production has significantly improved socioeconomic conditions of farming households. Most farmers willingly switched from rice to shrimp culture because of the higher income [20]. Environmental consequences were ignored due to the broader economic benefits, with shrimp referred to as “white gold” in Bangladesh, because of its high export value. Despite environmental concerns, shrimp culture seems to have had positive benefits for economic sustainability [3].

Shrimp production in Bangladesh has increased considerably from 56,569 t in 2010–2011 to 75,274 t in 2014–2015. The average annual growth rate of shrimp production is 5.38% [1,21]. Shrimp farming in low-lying coastal Bangladesh is extensive with farmers cutting a portion of dikes to allow tidal water to trap wild shrimp fry. Wild caught and hatchery produced shrimp postlarvae are also stocked. There are three types of shrimp farming systems in coastal Bangladesh: (1) shrimp alternate rice, (2) shrimp alternate salt, and (3) shrimp-only. In the shrimp alternate rice farming system, rice is produced during the monsoon when water salinity goes down and favors the growth of rice plants. In the shrimp alternate salt farming system, shrimp is grown during the monsoon when farms are inundated by tidal water while salt is produced during the dry season. Shrimp-only culture is practiced where water salinity is comparatively high for a period of 6–9 months annually and rice farming is not possible because of water salinity [3].

2.2. Mangrove forests in Bangladesh

Globally, Bangladesh is ranked 9th in mangrove area, covering 3% of the world's mangrove forests [11]. The Sundarbans is the largest continuous mangrove forest in the world, covering an area of over one million ha, located along the mouth of the Bay of Bengal between Bangladesh (60%) and India (40%). The Sundarbans in Bangladesh covers an area of 601,672 ha, of which 414,259 ha (70%) of land and 187,413 ha (30%) of water [22]. The Sundarbans lies on the delta of the Ganges, Brahmaputra, and Megna rivers within Bagerhat, Khulna, and Satkhira districts in southwest Bangladesh (Fig. 1). Including the Sundarbans, the total mangrove area in Bangladesh is 436,570 ha [23].

The Sundarbans mangrove forest contains diverse and rich natural resources, which has long been recognized for its wide range of biodiversity as it provides feeding, breeding, and nursery grounds for many ecologically and commercially important species [24,25]. The biodiversity of the Sundarbans includes about 334 plant species, 260 bird species, 210 fish species, 59 reptile species, 49 mammal species, and 8 amphibian species. In addition, the Sundarbans is the habitat for the largest population (400–450) of the Royal Bengal Tiger (*Panthera tigris tigris*), and many rare and endangered species, including the Ganges river dolphin (*Platanista gangetica*) and estuarine crocodile (*Crocodylus porosus*) [22]. The Sundarbans is also famous for its sundari (*Heritiera* spp.) tree. A transboundary forest of the Sundarbans is designated a Ramsar site since 1992, and a World Heritage Site of the United Nations Educational, Scientific and Cultural Organization (UNESCO) since 1997 [11].

The Sundarbans in Bangladesh provides a wide range of ecosystem goods and services, including climate regulation, coastal protection, fisheries, fuel, medicine, nutrient cycling, shelter, timber, and tourism [25]. According to Barbier [26], the total annual value of mangrove ecosystem services is US$10,158–12,392 per ha in Thailand. At this rate, the annual economic value of mangroves in Bangladesh is over US $4.43 billion (Table 1). Overall, mangrove ecosystem services have an important role in coastal economies of Bangladesh, supporting human wellbeing, including livelihoods, income, and food supply [27]. The livelihoods of over 3.5 million people are directly or indirectly dependent on the Sundarbans in Bangladesh [28,29].

2.3. Mangrove deforestation by shrimp cultivation

Mangrove forests are one of the world's most threatened tropical ecosystems [30]. Over 3.6 million ha of global mangrove forests were lost between 1980 and 2005 due to agriculture, aquaculture, overexploitation, pollution, tourism, and urbanization [11]. Among deforested mangroves, about 1.89 million ha (52%) were lost by coastal aquaculture, of which 1.4 million ha (38%) and 0.49 million ha (14%) of mangrove loss has resulted from shrimp culture and other forms of aquaculture, respectively. In Asia, coastal aquaculture accounts for 1.69 million ha of mangrove loss with shrimp farming accounting for 1.2 million ha of total deforestation [30].

Mangrove deforestation by shrimp cultivation is also common in Bangladesh. The unique Chakaria Sundarbans in southeast Bangladesh, which had 8500 ha of mangroves, was deforested due to shrimp culture [31,32]. Moreover, 290 ha of mangroves on Maiskhali Island and 133 ha of mangroves on Jaliardwip Island were cleared for shrimp ponds. In addition, 104 ha of mangroves on Matabar Island were lost due to shrimp cultivation. Around 670 ha of mangroves along the Naf River were also deforested for shrimp production [32]. According to Hossain [33], 1800 ha of mangroves in the Naf River estuary and off-shore islands were converted into shrimp farms. Overall, 10,000 ha of mangrove loss has resulted from shrimp culture in Bangladesh (Table 2). According to Shahid and Islam [32], over 9700 ha of mangrove loss has been attributed to shrimp culture since 1975. A recent study reported that mangroves in Bangladesh declined from 452,444 ha in 1976 to 441,455 ha in 2010 [34]. When mangroves are cleared for shrimp ponds, land values decrease by approximately US$10,000 per hectare [26]. At this rate, the annual economic value of mangrove loss to shrimp culture in Bangladesh is over US$100 million. It is, therefore, more valuable and economically profitable to conserve mangroves than shrimp culture [35]. In recent years, however, Bangladesh has made tremendous progress on mangrove conservation [11,12].

3. Mangrove deforestation and blue carbon emissions

3.1. Blue carbon ecosystems

Blue carbon[4] is the carbon stored, sequestered, and released from coastal and marine ecosystems, including mangroves, salt marshes, and seagrasses [14,16,36]. These three habitats are commonly referred to as blue carbon ecosystems. Globally, blue carbon ecosystems are about 51 million ha that store 11.5 billion tons of carbon, of which the highest blue carbon pool[5] is mangroves (6.5 billion tons) [15]. Policy initiatives on blue carbon have recently started as policymakers and scientists are increasingly cooperating on developing blue carbon concept to benefit

[4] The colors of carbon are fossil fuels “brown carbon”, dust particles “black carbon”, terrestrial ecosystems “green carbon”, and coastal and marine ecosystems “blue carbon” [36].

[5] A carbon pool is a natural or artificial reservoir that accumulates and stores some carbon-containing chemical compound for an indefinite period.

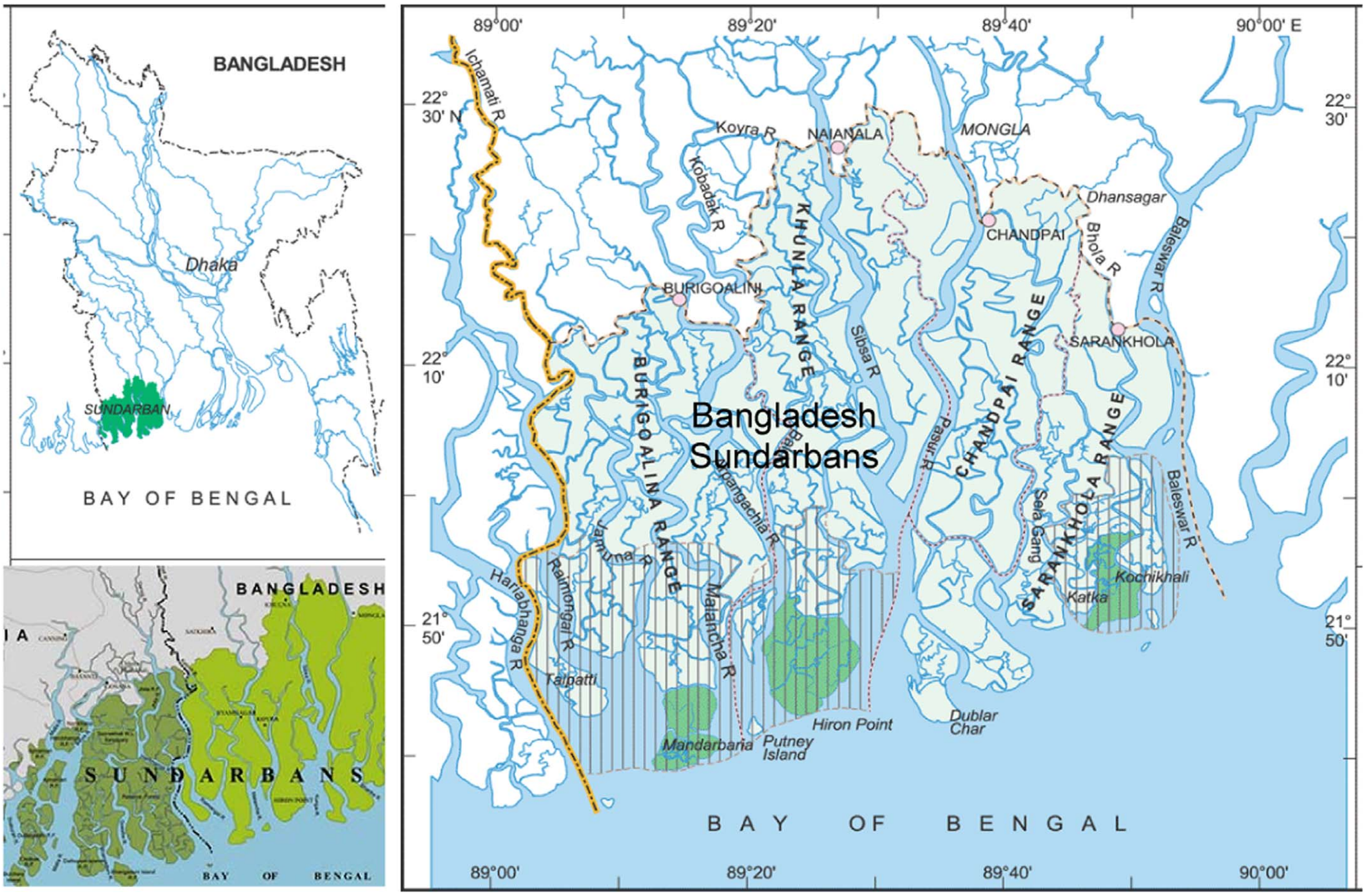

Fig. 1. Map of Bangladesh showing the Sundarbans mangrove forest.

Table 1
Mangrove forests in Bangladesh with its value of ecosystem services.

Feature	Statistics	Reference
Bangladesh position in global mangrove area	9th	FAO [11]
Mangrove forest area in Bangladesh (ha)	436,570	Giri et al. [23]
Bangladesh Sundarbans mangrove forest area (ha)	414,259	UNESCO [22]
Sundarbans covers Bangladesh mangrove area (%)	95	This study
Value of mangrove ecosystem services (US $/ha/yr)	10,158–12,392	Barbier [26]
Total value of mangrove ecosystem services in Bangladesh (US$/yr)	4.43–5.41 billion	This study

Table 2
Loss of mangrove forests to shrimp farms in coastal Bangladesh.

Mangrove forest	Area lost (ha)	Reference
Chakaria Sundarbans	8500	Hossain et al. [31]; Shahid and Islam [32]
Mangrove forest along the Naf River	667 or 1800[a]	Shahid and Islam [32]; Hossain [33]
Mangrove forest on Maiskhali Island	290	Shahid and Islam [32]
Mangrove forest on Jaliardwip Island	133	Shahid and Islam [32]
Mangrove forest on Matabar Island	104	Shahid and Islam [32]
Total	≈ 10,000	This study

[a] This figure included mangroves in off-shore islands.

coastal ecosystems [37].

In Bangladesh, blue carbon ecosystems comprise an estimated 2.1 million ha, of which 0.44 million ha (21%) is mangroves, 0.11 million ha (5%) is salt marshes, 0.66 million ha (32%) is seagrasses, and 0.89 million ha (42%) is river-estuaries suitable for seagrasses [38]. Blue carbon is emerging as a new option that can assist economic development in Bangladesh. Blue carbon ecosystems could play a crucial role in supporting ecosystem services. On average, the annual economic value of coastal ecosystem service product in Bangladesh is over US$6.25 billion [39]. Blue carbon plays a crucial role in regulating climate, and thus, conservation of blue carbon ecosystems can reduce the impacts of climate change [15,36].

3.2. Blue carbon sequestration and storage in mangroves

Globally, the blue carbon sequestration[6] rate is about 53 million tons annually, of which 16 million tons (30%) is by mangroves [15]. Mangrove forests sequester blue carbon at the rate of 1.15–1.39 t/ha annually [15,36,40]. At this rate, the annual blue carbon sequestration by mangrove forests in Bangladesh is over 0.50 million tons (Table 3). According to Chowdhury et al. [38], annual blue carbon sequestration by mangroves in Bangladesh is 0.56 million tons or 2.08 million tons of CO_2 as one ton of carbon becomes 3.67 t of CO_2 in the atmosphere.

Mangroves store[7] carbon in the soils, the living biomass above and below ground, and the non-living biomass [41,42]. Over 80% of the

[6] Carbon sequestration is the process of increasing the carbon content of a reservoir other than the atmosphere. Sequestration is the removal of atmospheric CO_2 through biological (photosynthesis) or geological (storages in underground reservoirs) processes.

[7] Carbon capture and storage is a process consisting of separation of CO_2 from its sources, transport to a storage location, and long-term isolation from the atmosphere.

Table 3
Blue carbon ecosystems in Bangladesh, focusing on mangrove forests with its blue carbon sequestration, storage, and emissions.

Element	Statistics	Reference
Total area of blue carbon ecosystems (million ha)	2.1	Chowdhury et al. [38]
Total area of mangrove forests (million ha)	0.44	Giri et al. [23]
Blue carbon sequestration rate by mangroves (t/ha/yr)	1.15–1.39	Siikamäki et al. [15]; Nellemann et al. [36]; Bouillon et al. [40]
Total blue carbon sequestration by mangroves (million t/yr)	0.50–0.61	This study
Mangroves store blue carbon (t/ha)	160–360	Rahman et al. [45]
Total blue carbon store in mangroves (million t)	70–158	This study
Blue carbon emissions from conversion of mangroves to shrimp farms (t/ha)	661–1135	Kauffman et al. [42]
Total loss of blue carbon from 10,000 ha deforested mangroves to shrimp farms (million t)	6.61–11.35	This study

mangrove's blue carbon stock is in the soils. Globally, mangrove soils contain about 5 billion tons of blue carbon within a 1 m soil depth [43]. In the Bangladesh Sundarbans, about 55 and 36 million tons of blue carbon are stored in the below ground and above ground respectively, resulting in total blue carbon stock of 91 million tons [44]. The Sundarbans mangrove forest stores 160–360 t/ha of blue carbon depending on vegetation types and salinity [45], which for Bangladesh adds about 70–158 million tons of blue carbon (Table 3). According to Humanitywatch [46], the Sundarbans in Bangladesh can capture about 56 million tons of carbon, worth at least US$1.87 billion in the international market.

3.3. Mangroves to shrimp farms: blue carbon emissions

The conversion of mangroves to shrimp farms increases blue carbon emissions. Cutting down mangroves to shrimp farms releases significant amounts of blue carbon and depletes storage facilities. When mangroves are converted to shrimp ponds, the large stores of blue carbon in the soils and biomass of mangrove ecosystems are exposed and released as CO_2 into the atmosphere. The emissions from 1 ha of mangrove forest converted to shrimp pond are equivalent to the emissions of about 5 ha of tropical evergreen forest conversion and 11.5 ha of tropical dry forest conversion. Blue carbon stocks of abandoned shrimp ponds are 95 t/ha, about ~11% that of mangroves. Potential loss of blue carbon from the conversion of mangroves to shrimp farms ranges from 661 to 1135 t/ha [42]. At this rate, the loss of blue carbon stock from 10,000 ha of deforested mangroves to shrimp farms in Bangladesh is ranging from 6.61 to 11.35 million tons (Table 3). Globally, the blue carbon emission rate is 58.7 million tons annually, of which 33.5 million tons (57%) derives from mangrove losses [15].

Clearly, blue carbon emissions from mangrove deforestation by shrimp cultivation are linked to anthropogenic climate change (Fig. 2). Although Bangladesh is contributing only 0.19% to the global CO_2 emissions [47], it is expected to increase CO_2 emissions 15 times by 2050 [48]. In the future, Bangladesh could be an important country for blue carbon emissions because of potential conversion of blue carbon ecosystems, including the destruction of mangrove forests for shrimp cultivation. Devastating effects on mangroves from the expansion of shrimp cultivation could increase blue carbon emissions. High blue carbon emissions could augment climate change that may have severe effects on coastal communities as Bangladesh is ranked 6th in 2016 among countries vulnerable to climate change [49].

4. Impacts of climate change

4.1. Punch back to shrimp farming

Shrimp farming in coastal Bangladesh has been accompanied by recent concerns over climate change. Different climatic variables including coastal flooding, cyclone, drought, rainfall variation, salinity, sea level rise, and sea surface temperature have had adverse effects on shrimp production [50]. Changes in these climatic variables have detrimental effects on the ecosystem of shrimp farms, and thus, affect

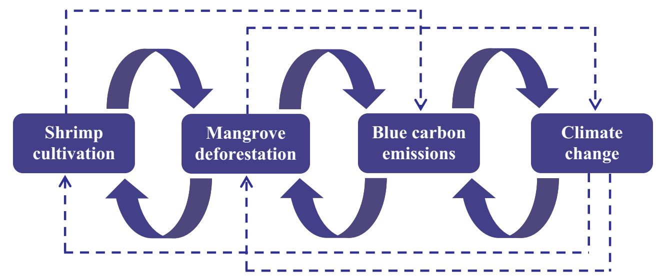

Fig. 2. Forward and backward linkages between shrimp cultivation, mangrove deforestation, blue carbon emissions, and climate change; mangrove deforestation by shrimp cultivation increases blue carbon emissions that cause climate change; conversely, climate change increases blue carbon emissions through devastating effects on mangroves and shrimp farms.

survival, growth, and production of shrimp. Rainfall variation can cause havoc on shrimp farms due to the increased risk of flood and drought. Shrimp culture is vulnerable to floods as farmers often lose their harvest. Droughts also reduce water availability to grow shrimp. Coastal aquaculture is also extremely vulnerable to cyclones with tidal surges that destroy shrimp farms. Increased water salinity leads to change in the ecosystems of shrimp farms. Sea level rise is also likely to have detrimental effects on low-lying shrimp farms. Last, but not least, increased water temperature has adverse effects on shrimp production [50].

Mangroves are significant for resilience to climatic effects on shrimp cultivation. Mangrove forests protect shrimp farms from tidal surges by providing an active barrier to cyclones and reduce wave energy. Mangroves are considered in protecting from cyclonic effects, shoreline erosion, and coastal flooding as they can prevent floodwater due to their capability to absorb wave energy and stabilize coastal land [18,51]. In areas adjacent to shrimp farms, nutrient outflow can be mitigated by mangroves due to maintaining surrounding water quality by filtering minerals, nutrients, pollutants, and sediments [52,53].

However, mangroves are under threat from global climate change including sea level rise [54]. Sea level appears to be rising by 15.9–17.2 mm each year in coastal Bangladesh [55], while global sea level rises 2–3 mm each year [56]. Sea level rise along the Bangladesh coast is higher than the global rate, which may alter hydrological conditions of the Sundarbans [57]. Sea level could rise 1 m by 2100 [58], and such a rise could inundate the Sundarbans [59]. Since the 1970s, the Sundarbans in Bangladesh and India has lost 17,000 ha due to sea level rise [60].

4.2. Effects on mangrove fisheries

Climate change has profound effects on ecosystems, species, and populations in the Sundarbans, with severe consequences for fisheries [59]. Cyclones with tidal surges often destroy habitat structure of the Sundarbans. Habitat alteration could reduce the abundance of many fish species [24]. The impact of rainfall variation on fish habitat in the Sundarbans is becoming increasingly apparent [61]. The ecosystem of the Sundarbans is threatened by different types of pollutants and solid

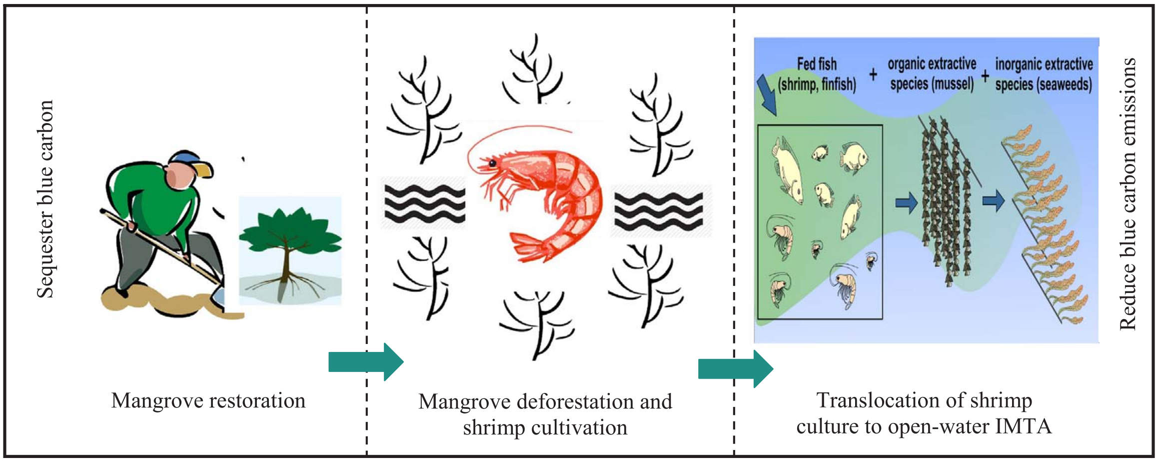

Fig. 3. Translocation of shrimp culture from deforested mangroves to open-water IMTA could help mangrove restoration.

particles run-off in floodwater [59]. Changes in water salinity may affect fish assemblages in tropical estuaries near mangroves [62]. Changes in water temperature may also provoke multiple effects on the Sundarbans, which may change the timing of migration and the spawning of fish [63]. The availability and catch of prawn and shrimp postlarvae around the Sundarbans has sharply declined due to climate change [64].

Ultimately, climate change with degradation of mangroves has serious effects on fish catch. In 2014–2015, total annual fish catch in the Sundarbans was estimated at 17,580 t, with an average annual yield of 99 kg/ha [1]. Whereas, total annual fish catch in the Sundarbans was much higher at 22,451 t in 2010–2011, with an average annual yield of 126 kg/ha [21]. According to MacKinnon and MacKinnon [65], deforestation of a hectare mangrove area nearby coastal fisheries may result in the loss of 480 kg of fish annually.

4.3. *Vulnerability of coastal communities*

Deforestation of mangroves makes shrimp farming communities more vulnerable to climate change and also has severe impacts on socioeconomic conditions of coastal fishing communities. The livelihoods of around 200,000 fishers are dependent on fisheries of the Sundarbans [28]. However, declining fish catch has severely affected livelihoods and income of coastal fishers [66]. More importantly, climate change has severe threats to lives and property in coastal communities. The frequency of cyclones has recently increased in coastal Bangladesh as cyclone Sidr (2007), Nargis (May 2008), Bijli (April 2009), Aila (May 2009), Viyaru (May 2013), Komen (July 2015), and Ruano (May 2016) devastated coastal life. About 14.6 million people are vulnerable to inundation from cyclonic surges, and this number will increase to 18.5 million by 2050 [67]. Moreover, coastal communities are vulnerable to sea level rise as Bangladesh lies just less than 2 m above sea level [56]. A 45 cm rise in sea level would inundate 11% of Bangladesh, making millions of people homeless [68]. Saltwater intrusion is an increasing problem that has reached over 100 km inland [69]. About 1.06 million ha of land in coastal Bangladesh has affected by salinity [70], which is predicted to reach two million ha by 2050 [71]. Increased soil and water salinity has already affected food production.

Mangroves protect groundwater salinity, which prevents the entry of saltwater to inland areas [72]. Mangroves are significant for protecting against tidal surges [18]. Evidence has suggested that areas with intact mangroves suffered less damage from storms [73]. The cyclone protection services of mangroves in India became apparent for reducing human death [74]. Mangroves can enhance sea defences, and thus, mangrove restoration is a priority adaptation strategy from sea level rise [75].

5. Adaptation strategies

5.1. *Integrated Multi-Trophic Aquaculture (IMTA)*

IMTA is a process of growing different species of finfish and shellfish with seaweeds from different trophic levels in an integrated farm for increasing productivity and profitability through efficient recycling and reuse of nutrients. The principle of IMTA is the co-cultivation of fed fish, organic extractive species, and inorganic extractive species [76–78]. IMTA is currently operated in over 40 countries on experimental and commercial basis, including Canada, Chile, China, Japan, the USA, and many European countries [77]. The translocation of shrimp culture from mangroves to open-water IMTA could reduce blue carbon emissions, which in turn sequester and store blue carbon through the restoration of mangroves (Fig. 3). Open-water IMTA in coastal Bangladesh can help to restore mangroves through plantation, regeneration, and avoiding deforestation. Seaweed cultivation in IMTA could also help to sequester blue carbon through photosynthesis [79].

Translocation of shrimp culture from mangroves to open-water IMTA in coastal Bangladesh can be environmentally friendly. IMTA can hinder intensive fishing if IMTA could be placed in shrimp postlarvae fishing sites. Indiscriminate fishing of postlarvae with high levels of bycatch has serious impacts on biodiversity and ecosystems in coastal Bangladesh [80]. IMTA can increase biodiversity at aquaculture sites [81], which in turn enhances the resilience of coastal ecosystems [82,83]. IMTA could increase the range of response and adaptation options to climate change. IMTA may not be affected by flood, sea level rise, salinity variation, and increased water temperature. IMTA can adapt to variation of water salinity as mollusks, seaweeds, and shrimp are able to tolerate wide range of salinity [84]. Seaweeds in IMTA can also help to keep water clean and cool due to absorption of pollutants, sediments, and toxic substances [79].

5.2. *Mangrove restoration for blue carbon sequestration*

There is a growing recognition of the importance of mangroves for mitigating climate change by sequestering and storing blue carbon [13,14]. Mangrove restoration can be an option for climate change mitigation through blue carbon sequestration [41,85]. Blue carbon could be seen as an opportunity for restoration and conservation of mangroves to promote ecosystem-based mitigation and adaptation to climate change [86]. Mangrove restoration is therefore a significant climate change mitigation action in coastal Bangladesh.

Mangrove restoration would compensate mangrove loss by shrimp culture and climatic effects. Mangrove restoration usually relies on mangrove plantation alone regeneration. Depending on the type of degradation, there are two major types of mangrove restoration: (1)

mangrove restoration following anthropogenic degradation, and (2) mangrove restoration following natural disturbances [87]. Although both types of mangrove restoration are crucial for Bangladesh, site selection in mangrove restoration could be focused within shrimp farming areas where mangroves were deforested. Mangrove ecology and economic support are also needed for the successful restoration of mangroves. Socioeconomic and ecological issues with cost evaluation to design and construction are important for mangrove restoration [88].

5.3. Reducing Emissions from Deforestation and forest Degradation (REDD +)

Mangrove restoration as well as reforestation and afforestation,[8] facilitated by the REDD+ (plus for forest conservation) initiatives, has the potential for conservation of mangroves [12,89,90]. The REDD+ program would restore mangroves, which in turn increases options for adaptation to climate change through blue carbon sequestration [13,15,18]. The REDD+ approach is suitable for mitigating greenhouse gas emissions by economic support for preventing mangrove deforestation and degradation [90]. REDD+ can perform a major role in reducing anthropogenic emissions, and thus, help to mitigate climate change [91]. If REDD+ were applied worldwide, a maximum of 2.5 billion tons CO_2 emissions could be avoided annually [92].

Globally, a number of REDD+ projects have recently concentrated on mangrove restoration for climate change mitigation through carbon offsets [93,94]. REDD+ could play an important role in restoring mangrove forests to compensate for mangrove area lost to coastal aquaculture [35,95]. If REDD+ rehabilitated one-fourth of deforested mangrove area by shrimp culture in Bangladesh, at least 2875 t of blue carbon could be sequestered annually. Similarly, if REDD+ rehabilitated all deforested mangrove area by shrimp culture, over 11,500 t of blue carbon could be sequestered annually (Table 4). A national REDD + readiness roadmap was approved in 2012 by the Ministry of Environment and Forest. A Collaborative REDD/IFM (Improved Forest Management) Sundarbans Project (CRISP) in Bangladesh is aimed to conserve mangrove forests to reduce emissions of about 6.4 million tons of CO_2 over a 30-year period [96]. It is anticipated that a REDD+ project may have positive impacts on the Sundarbans.

6. Future prospects

The development of IMTA, mangrove restoration, and the implementation of REDD+ in coastal Bangladesh could bring a wide range of social, economic, and environmental benefits, which in turn may help with adaptation to climate change. High-value seafood production (mollusks, seaweeds, and shrimp) in IMTA and mangrove restoration could be an option for adding economic value to coastal waters and mangrove forests through livelihood opportunities and income for the poor. Mangrove restoration through REDD+ is also significant for sustainable shrimp cultivation to provide socioeconomic benefits among farming households and associated groups (e.g., postlarvae fishers, input suppliers, and market actors). Mangrove restoration would also provide wider benefits to coastal communities, including food, income, and sustainable livelihoods.

Despite potential benefits, the implementation of the proposed adaptation strategies could face social, economic, and environmental challenges. Social acceptability and economic viability of IMTA will need to be determined for its development in coastal Bangladesh. IMTA will also face environmental and technological problems due to its operation in open-water conditions [97]. User conflicts may also arise for access to coastal waters as they are considered and used as common-pool resources. Moreover, open-water IMTA could affect the livelihood of coastal fishers. Nevertheless, community-based fisheries management can be an effective means to sustain the livelihood of fishers through better access to water and enhanced water management [98].

Mangrove restoration is also complicated and challenging in coastal Bangladesh because of the effects of intensive human intervention in the context of very poor socioeconomic conditions [87]. Community-based mangrove restoration project may help to overcome social, economic, and ecological challenges. The local community can be involved in action for mangrove restoration projects. Community participation in forest management can help with the conservation of the Sundarbans [99]. Involving coastal communities is also significant for the implementation of REDD+ to conserve mangrove forests. However, a legal and institutional review and reform is needed for the successful implementation of REDD+ project [100].

Despite various challenges, institutional support is needed for the implementation of the proposed adaptation strategies. Support from government and non-governmental organizations (NGO), key stakeholder involvement, and private sector investment in IMTA and mangrove restoration are needed. Training on IMTA through demonstration and pilot projects is likely to be the most successful way of technology transfer. Although, blue carbon is considered a cost-effective option to achieve positive climate change adaptation outcomes [37], public-private partnership is needed to finance mangrove restoration and REDD+ implementation. Moreover, the motivations of mangrove restoration and REDD+ implementation require awareness of coastal communities, which can be provided through extension services, training programs, and technical assistance.

Table 4
Potential for sequestering blue carbon through restoration of deforested mangroves to shrimp farms facilitated by REDD+.

Mangrove area lost to shrimp aquaculture (ha)	Restoration of mangrove area (%) through REDD+	Restoration of mangrove area (ha) through REDD+	Blue carbon sequestration rate (t/ha/yr) by mangroves[1]	Total blue carbon sequestration (t/yr)
	25	2500		2875–3475
10,000	50	5000	1.15–1.39	5750–6950
	75	7500		8625–10,425
	100	10,000		11,500–13,900

[1]Source: Siikamäki et al. [15]; Nellemann et al. [36]; Bouillon et al. [40].

7. Conclusions

Shrimp farming is currently one of the most important sectors of the national economy in Bangladesh due to earning valuable foreign exchange, contributing to food production, and diversifying coastal livelihoods. However, shrimp culture has devastating effects on mangrove forests, which is one of the key reasons for blue carbon emissions. Carbon emissions are the dominant cause of climate change, and Bangladesh is one of the most vulnerable countries to climate change. Mangrove deforestation with climate change has adverse effects on shrimp cultivation and socioeconomic conditions of coastal communities. It is, therefore, necessary to reduce blue carbon emissions from mangrove deforestation by shrimp cultivation to tackle climate change.

Some adaptation strategies including IMTA, mangrove restoration, and REDD+ could help to reduce blue carbon emissions for climate change mitigation in coastal Bangladesh. Translocation of shrimp culture from mangroves to open-water IMTA could reduce blue carbon emissions, while subsequent mangrove restoration could increase the storage of blue carbon. Moreover, mangrove restoration and seaweed cultivation in IMTA could help to increase blue carbon sequestration. Mangrove restoration by the REDD+ program has the potential for

[8] Mangrove restoration is the generation of mangrove forest ecosystems in areas where they have previously existed. Reforestation and mangrove restoration are often interchangeably used. However, afforestation means planting of new forests on lands that have not previously contained forests.

conservation of mangrove forests for resilience to climate change.

The implementation of the proposed adaptation strategies in coastal Bangladesh, however, requires institutional support including extension services, training programs, and technical assistance. All key stakeholders including government, NGOs, researchers, policymakers, and coastal communities must work together for the implementation of such adaptation strategies. Further research is also needed on mangrove restoration, shrimp cultivation, blue carbon sequestration, and climate change mitigation in coastal Bangladesh.

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