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Coastal aquaculture, mangrove deforestation and blue carbon emissions: Is REDD+ a solution?

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ABSTRACT

Globally, coastal aquaculture particularly shrimp farming has been under huge criticism because of its environmental impacts including devastating effects on mangrove forests. However, mangroves are ecologically and economically important forests, and the most carbon-rich forests in the tropics that provide a wide range of ecosystem services and biodiversity conservation. Carbon emissions are likely to have been the dominant cause of climate change and blue carbon emissions are being critically augmented through mangrove deforestation. Because of mangrove deforestation, different climatic variables including coastal flooding, cyclone, drought, rainfall, salinity, sea-level rise, and sea surface temperature have dramatic effects on coastal aquaculture. Mangrove forests have been instrumental in augmenting resilience to climate change. The "Reducing Emissions from Deforestation and forest Degradation (REDD)" program can help to restore mangroves which in turn increases options for adaptation to climate change. However, technical and financial assistance with institutional support are needed to implement REDD+.

1. Introduction

Aquaculture is one of the fastest growing food production systems in the world as the sector has expanded at an average annual rate of 8.6% over the last three decades. Global fish production reached 66.6 million tons in 2012, of which Asia accounted for 88.4%. About 41.9 million tons (63%) and 24.7 million tons (37%) of fish production were obtained from inland aquaculture and mariculture, respectively [1]. Coastal aquaculture, a part of mariculture, is the onshore and near-shore culture of brackish and saltwater fish including shellfish [2,3]. Globally, coastal aquaculture expanded rapidly in the 1980s and 1990s. Over the last decades, coastal aquaculture including shrimp farming has undergone a revolutionary development [4,5].

There have been considerable debate and argument on the impacts of coastal aquaculture on the environment, biodiversity, and society [3,5]. Globally, shrimp farming has been strongly criticized because of its socioeconomic and environmental impacts [4,6–10]. Rapid loss of mangroves has accelerated over the last decades, and coastal aquaculture including shrimp farming is one of the key reasons [11–14]. Driven by high economic return associated with growing demand in the international market, unplanned and unregulated 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 [12,15].

Mangroves are the most carbon-rich forests in the tropics [16–20]. On average, mangroves store 3–4 times more carbon than tropical forests [17]. At the same time, mangrove deforestation rates are significantly higher than average rates of global forest loss [12]. Mangrove deforestation causes carbon emission and reduces carbon sequestration[1] [20]. Carbon emissions with other greenhouse gases (CH_4, N_2O) are likely to have been the dominant cause of climate change [21]. To tackle climate change, it is therefore crucial to stop carbon emissions from the deforestation and degradation[2] of mangroves [16,17,20,22].

The conservation of mangrove forests can help to reduce carbon emissions [18,23]. It is argued that the "Reducing Emissions from Deforestation and forest Degradation (REDD)" program can help to sequester carbon in mangroves [17,19,24–26]. This review

[1] In the atmosphere, carbon is attached to O_2 and becomes CO_2 which is a greenhouse gas, causing trap heat in the atmosphere [117]. One ton of carbon becomes 3.67 t of CO_2 in the atmosphere. Carbon sequestration is the process of increasing the carbon content of a reservoir or pool other than the atmosphere.

[2] "Deforestation" is defined as the permanent conversion of forest to another land cover (croplands, pastures), while "degradation" is a lowering of biomass density within a forest cover, such as wood harvesting.

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Table 1
Milestones for the development of REDD+.

Year	UNFCCC held	Development
1997	3rd COP: Kyoto, Japan	Adopted Kyoto Protocol
2005	11th COP: Montreal, Canada	The concept of RED emerged
2006	12th COP: Nairobi, Kenya	Plan to work on adaptation to climate change
2007	13th COP: Bali, Indonesia	The RED concept expanded to REDD
2008	14th COP: Poznan, Poland	Methodological progress on REDD
2009	15th COP: Copenhagen, Denmark	REDD features in the Copenhagen Accord
2010	16th COP: Cancun, Mexico	REDD converted to REDD+
2011	17th COP: Durban, South Africa	Agriculture included as a possible sector
2012	18th COP: Doha, Qatar	Decision on financial incentives to developing countries
2013	19th COP: Warsaw, Poland	Decision on REDD+ implementation process
2014	20th COP: Lima, Peru	Progress on UN-REDD program
2015	21th COP: Paris, France	Decision on conservation of forests through REDD+ for enhancing carbon stocks

paper highlights key issues in reducing carbon emissions from mangroves through REDD+. The impacts of climate change on coastal aquaculture that occur with the deforestation of mangroves are also discussed. Finally, this paper offers some preliminary conclusions about the implementation of REDD+ for the restoration of mangrove forests.

2. Reducing emissions from deforestation and forest degradation (REDD)

2.1. From RED to REDD+

Although greenhouse gas emissions increase with deforestation, controversies arose over the inclusion of forest conservation under the Kyoto Protocol that was adopted at the 3rd Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in 1997 [27]. In 2005, the concept of "Reduced Emissions from Deforestation (RED)" in developing countries was first emerged at the 11th COP of the UNFCCC agenda in Montreal [28]. In 2006, at the 12th COP of the UNFCCC in Nairobi, a program on impacts, vulnerability, and adaptation to climate change was finalized [29]. In 2007, at the 13th COP of the UNFCCC in Bali, the concept of RED was expanded to REDD with "forest degradation" included. In 2008, at the 14th COP of the UNFCCC in Poznan, methodological issues relating to REDD were discussed. At the 15th COP of the UNFCCC in 2009, REDD emerged as a critical component in the Copenhagen Accord. In 2010, at the 16th COP of the UNFCCC in Cancun, an official agreement was achieved on REDD+. The plus (+) was formally added for the conservation and enhancement of the forest carbon stock and the sustainable management of forests [30]. In 2011, at the 17th COP of the UNFCCC in Durban, agriculture was included as a possible driver of deforestation and degradation [28]. In 2012, at the 18th COP of the UNFCCC in Doha, incentives relating to REDD+ in developing countries were discussed. In 2013, at the 19th COP of the UNFCCC in Warsaw, several decisions on REDD+ were adopted regarding finance, institutional arrangement, and methodological guidance to make REDD+ fully functional [31]. In 2014, at the 20th COP of the UNFCCC in Lima, progress on the United Nations REDD (UN-REDD) program fund was discussed. In 2015, at the 21th COP of the UNFCCC in Paris, developing countries were encouraged to conserve forests for enhancing carbon stocks. The steps for the development of REDD+ are summarized in Table 1.

2.2. Significance of REDD+

REDD+ is a potentially low-cost contribution to climate change mitigation that has drawn attention at local, national, and international levels. REDD+ can play a significant role in reducing anthropogenic[3] emissions, and thus, help to reduce climate change [22]. The REDD+ mechanism is appropriate to mitigate greenhouse gas emissions by financial support for avoiding mangrove deforestation and degradation [28]. Successful implementation of REDD+ must address and overcome challenges, including direct and indirect costs of forest conservation [32,33]. The UN-REDD program offers developing countries extensive support on deforestation and forest degradation issues. Today, there are several UN-REDD pilot projects in many countries worldwide. If REDD+ were implemented globally, a maximum of 2.5 billion tons CO_2 emissions could be avoided annually [34].

REDD+ is an example of Payments for Ecosystem Services (PES) as REDD+ emerged as a scaled-up version of PES [35]. PES and REDD+ can provide wider economic benefits to local communities through enhancing the sustainability of natural resource management. REDD+ strengthens to reduce carbon emissions while PES retains its broad range of ecosystem services and biodiversity conservation [36]. Nevertheless, REDD+ provides a great opportunity for the conservation of biodiversity and ecosystem services [37,38]. According to a decision under the United Nations Convention on Biological Diversity held in Nagoya in 2010, aquaculture is one of the targets of the strategic plan for conservation of biodiversity through REDD+ by 2020 [39]. REDD+ also aims for poverty alleviation, sustainable livelihoods, and protecting indigenous people's right [40]. Ecosystem-based adaptation to climate change may help to achieve REDD+ objectives. The implementation of REDD+ activities aims to maintain and enhance ecosystem services, significant for societal adaptation [30]. Knowledge of indigenous forest communities is also important to implement REDD+ [41]. International cooperation is needed to implement REDD+ to combat climate change and deforestation [42].

3. Mangrove deforestation and loss of ecosystem services

3.1. Mangrove deforestation through coastal aquaculture

Total global forest area is just over 4 billion ha, about 31% of land area. Globally, the total mangrove area is 15.6 million ha[4], just 0.39% of forest area. Mangroves occur in 112 countries worldwide, mainly in the tropics and sub-tropics. However, 47% of the global mangrove area is found in 5 countries: Indonesia, Brazil, Nigeria,

[3] Anthropogenic is something that is caused or made by humans. Anthropogenic climate change refers to the production of greenhouse gases emitted by human activities.

[4] Considerable variation of global mangrove area was found; for example, Giri et al. [118] reported that global mangrove area was 13.7 million ha, while Spalding et al. [119] noted 15.2 million ha.

Table 2
Features of global mangrove forests with its losses through coastal aquaculture.

Feature	Information	Reference
Global forest area (ha)	4 billion	FAO [43]
Forest cover of global land area (%)	31	FAO [43]
Global mangrove area (ha)	15.6 million	FAO [43]
Mangroves cover of global forest area (%)	0.39	FAO [43]
Mangroves exist in number of countries	112	FAO [43]
Annual mangrove area lost rate 1980–2005 (%)	0.66–1.04	FAO [43]
Total mangrove area lost 1980–2005 (ha)	3.6 million	FAO [43]
Mangrove area lost to shrimp culture (ha)	1.4 million	Valiela et al. [44]
Mangrove area lost to other aquaculture (ha)	0.49 million	Valiela et al. [44]
Total mangrove area lost to coastal aquaculture (ha)	1.89 million	Valiela et al. [44]
Mangrove area lost to coastal aquaculture (%)	52	Valiela et al. [44]
Economic value of mangrove loss (US $/ha/yr)	2000–9000	UNEP-WCMC [52]
Total economic value of mangrove loss to aquaculture (US$/yr)	3.78–17.01 billion	This study

Australia, and Mexico [43]. Mangrove forests are one of the world's most threatened tropical ecosystems [44]. It is estimated that mangrove forest has declined by 30–50% over the past half century [12,17,45,46]. Over 3.6 million ha of mangroves were lost between 1980 and 2005 due to agriculture, aquaculture, overexploitation, pollution, tourism, and urbanization. Annual global rates of mangrove loss declined from 1.04% in the 1980s to 0.66% between 2000 and 2005 [12]. In addition to loss from direct human intervention, about 10–15% of mangroves could be lost through climate change by 2100 [47]. It is predicted that all mangroves could be lost in the next 100 years [46].

According to Valiela et al. [44], about 1.4 million ha (38%) and 0.49 million ha (14%) of global mangrove loss has resulted from shrimp culture and other forms of coastal aquaculture, respectively. Most countries have recently banned the conversion of mangroves to shrimp farming due to concerns about environmental impacts [12]. However, very few abandoned shrimp farms revert to mangrove ecosystems due to significant changes in hydrological and environmental conditions. Moreover, the discharges (chemicals, nutrients, and pollutants) from coastal aquaculture continue to have detrimental impacts on adjacent mangroves [15].

3.2. Threatening ecosystem services

Mangroves are ecologically and economically important forests for the planet [20]. Mangroves provide a wide range of ecosystem goods and services, including provisioning (e.g., biodiversity, fiber, fisheries, fodder, food, fuel, medicines, tannins, and timber), regulating and supporting (e.g., climate regulation, coastal protection, controlling erosion, maintaining water quality, nutrient cycling, soil stabilization, and supporting coral reefs and seagrasses), and cultural services (education, heritage, recreation, research, and tourism) [15,48]. Mangrove forests have long been recognized for their wide range of biodiversity due to using feeding, breeding, and nursery grounds for many ecologically and commercially important species, including crabs, fish, mollusks, oysters, and shrimps, and provide habitats for many species of amphibians, birds, crustaceans, and mammals [12,49]. Biologically rich mangrove ecosystems provide important goods and services that support human well-being, including livelihoods, income, food security, health services, poverty reduction, and social sustainability [12,15,50,51]. Overall, mangrove ecosystems have an important role in coastal economies. The annual economic value of mangrove ecosystem services has been estimated at US$2000–9000 per ha [52]. At this rate, the annual economic value of mangrove loss from aquaculture amounts to US$3.78–17.01 billion (Table 2). Such loss of mangrove ecosystem services has adverse effects on coastal communities and national economies.

The ever increasing human pressure on mangroves threatens ecosystem services. Over 100 million people live within 10 km of significant mangrove areas, and this number is predicted to increase about 120 million by 2015 [15]. The loss of mangroves through aquaculture has adverse impacts on the livelihoods and income of coastal communities. Loss of mangroves not only threatens coastal aquaculture, but also mangrove fisheries. Reduced fish catch has an impact on fish consumption and protein intake by coastal communities. Lower nutrient intake and reduced food consumption may worsen health conditions of coastal communities. Mangrove losses may have direct impacts on food security in coastal communities by reducing cash and subsistence income [12,15].

4. Mangrove deforestation and blue carbon emissions

Mangroves play a significant role as blue carbon[5] sinks. Blue carbon is the organic carbon stored, sequestered, and released from coastal and marine ecosystems, including mangroves, salt marshes, and seagrasses [18,20,23,25,53,54]. Global coverage of blue carbon ecosystems are approximately 51 million ha [55], of which 15.6 million ha (31%) is mangroves [43]. Coastal and marine ecosystems store about 11.5 billion tons of blue carbon, of which 6.5 billion tons (57%) in mangroves (Fig. 1). According to Donato et al. [17], mangroves store 4–20 billion tons of blue carbon globally. Over 80% of the mangrove's blue carbon stock in the soils. Globally, mangrove soils contain 5 billion tons of blue carbon within 1 m soil depth [56]. On average, mangroves store around 1023 t of blue carbon per ha in their biomass and under soil [17].

Blue carbon emissions are being critically augmented due to devastating effects on mangroves [18,20,23,25,53,54]. Despite covering just 0.39% of total forest area [43], mangrove losses account for 10% of global emissions from deforestation [17]. Global annual blue carbon emission is 58.7 million tons, of which 33.5 million tons (57%) derives from mangrove losses [55]. According to Donato et al. [17], global annual blue carbon emission from mangroves ranged from 20 to 120 million tons.

The emissions from 1 ha of mangrove 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 [57]. Annual blue carbon emissions from land use change in mangroves to aquaculture ranged from 112 to 392 t/ha [17]. Blue carbon stocks of abandoned shrimp ponds were estimated at 95 t/ha, about ~11% that of mangroves. Potential loss of blue carbon stock from the conversion of mangroves to shrimp farms ranged from 661 to 1135 t/ha [57].

5. Mangrove deforestation, climate change and coastal aquaculture

Anthropogenic climate change with loss of mangroves has devastating effects on coastal aquaculture. The impacts of climate change on coastal aquaculture have been assessed with different climatic variables, including: (1) coastal flooding, (2) cyclone, (4) drought, (3) rainfall, (5) salinity, (6) sea-level rise, and (7) sea surface temperature [58,59]. Changes in these climatic variables

[5] Other forms of carbon are fossil fuels “brown carbon”, dust particles “black carbon”, and terrestrial ecosystems “green carbon”.

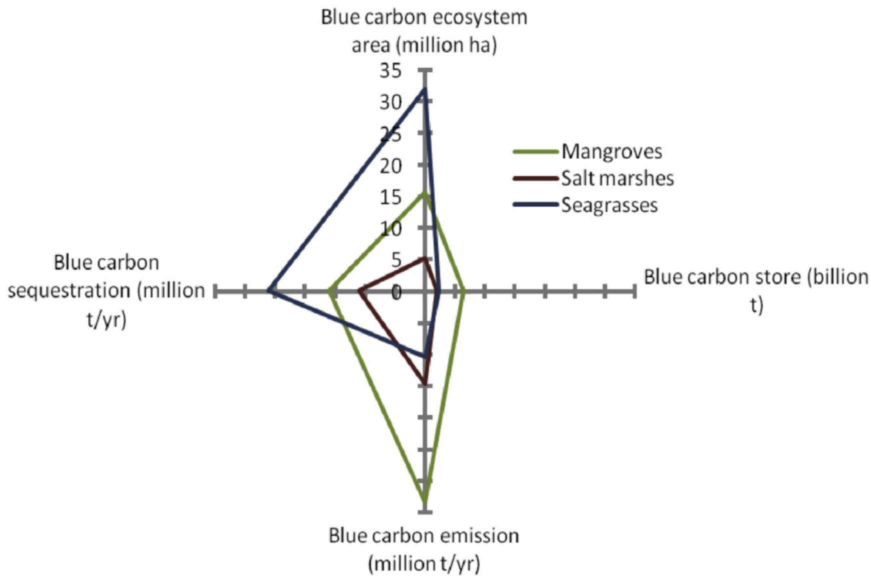

Fig. 1. Global blue carbon ecosystem area with its carbon store, emission, and sequestration by mangroves, salt marshes, and seagrasses; adapted from Siikamäki et al. [58].

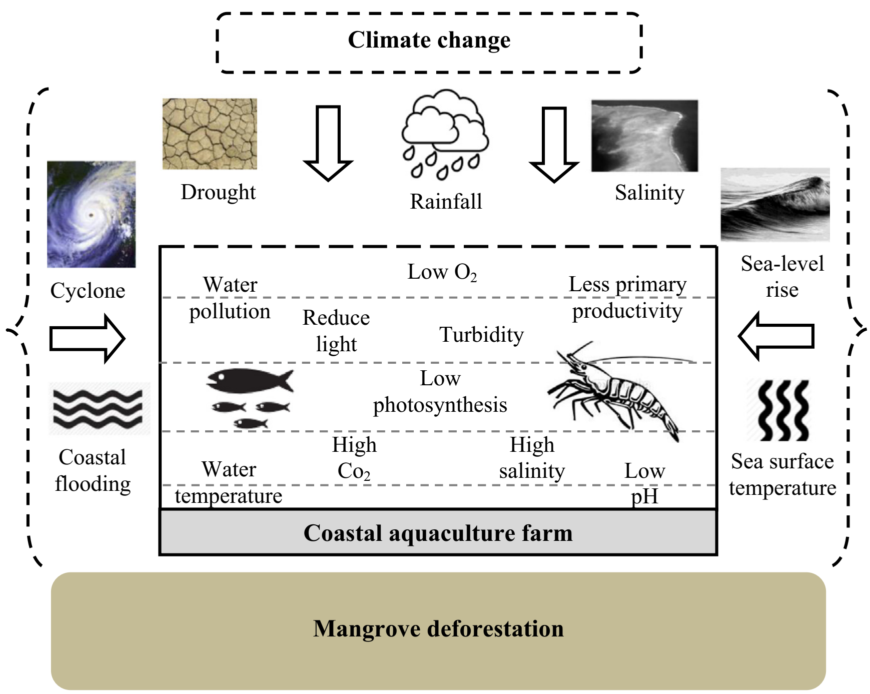

Fig. 2. Mangrove deforestation through coastal aquaculture and its consequences of climate change on the ecosystems of shrimp farms.

have severe effects on the ecosystem of fish farms (Fig. 2). Fish are highly sensitive to ecological conditions and changes in aquatic ecosystem have profound effects on their survival, growth, and production.

5.1. *Coastal flooding*

Flood is common in coastal areas due to cyclones with tidal surges and sea-level rise. Coastal aquaculture is extremely vulnerable to flood as harvest may be partially or completely lost. Floods also allow predatory fish with diseases and parasites to enter shrimp farms [58]. Water quality is affected by coastal flooding due to risks of contamination with toxic substances and land-based pollutants. Poor water quality and presence of toxins often cause shrimp disease [60]. Mangroves are significant in protecting coastal flooding as they can defend floodwater due to their ability to absorb and scatter wave energy and stabilize coastal land [25,61]. Mangroves maintain surrounding water quality by filtering minerals, nutrients, pollutants, and sediments from tidal and river waters. The physical structure of mangroves slows the water flow allowing clays, heavy metals, and sands to drop out of suspension in the water column [62–64]. In areas adjacent to shrimp culture, nutrient outflow can be mitigated by mangroves. Loss of mangroves increases the threat of coastal flooding to human safety and shoreline development [65].

5.2. *Cyclone*

Coastal aquaculture in tropical regions is vulnerable to violent storms and tropical cyclones, including hurricanes, tsunamis, and typhoons. In recent years, tropical cyclones devastated coastal aquaculture in South and Southeast Asia. The losses in the shrimp sector of Bangladesh caused by cyclone Sidr in 2007 were US$36 million [66]. In 2013, cyclone Pailin caused an estimated damage of US$57 million to shrimp farms in Odisha, India [67]. Deforestation of mangroves leaves coastal aquaculture more vulnerable to damage from cyclones because of no longer reduces wave energy without mangrove barriers [68]. Mangroves are very effective in buffering coastal settlements from tidal surges [61], and provide an effective barrier to cyclones [69]. In India, the cyclone protection services of mangroves were found to reduce both the death toll and economic losses from cyclones [70,71]. Community people in Panay Island, the Philippines believe that mangroves protect them from natural disasters including cyclones [72]. Although mangroves cannot completely protect from a tsunami, they reduce wave velocity to some degree, and thus, saving lives and property [47,73–75]. Coastal communities located behind intact mangroves suffered less damage from the tsunami in 2004 [76]. It is, therefore, generally agreed that conserving mangroves should buffer coastal communities from future tsunami events [77].

5.3. Drought

Drought seriously affects coastal aquaculture because of the lack of water to grow fish. Drought is associated with lack of precipitation and high temperatures [78]. Global warming accelerates the drying of land-surface as heat increases evaporation of moisture with the risk of drought [79]. An El Niño[6] event with strong warming can cause the monsoon to switch into a dry mode, resulting significant reductions in rainfall and severe droughts [80]. Reduction in primary productivity caused by drought could turn temperate ecosystems into carbon sources [81]. A major drought effect is the reduction of photosynthesis which can have impacts on carbon balance [82]. Seasonal drought may increase water temperature and salinity that adversely affect shrimp production [83]. Mangroves may provide resilience to climatic effects of droughts. Increasing mangrove productivity and biodiversity may protect from increased water temperature, salinity, CO_2, and changes in rainfall patterns [84,85]. A forestation project in Bolivia has been shown to reduce irregular rainfall [86].

5.4. Rainfall

Global warming can cause changes in rainfall patterns as the water holding capacity of air increases 6–7% for every 1 °C increase in temperature [78]. Heavy rainfall often reduces water temperature that affects the growth of fish as warmer conditions are suitable for recruitment. Fluctuations in water temperature with low salinity cause the outbreak of white spot syndrome virus in shrimp [87]. Intense rainfall often causes soil erosion and water turbidity in shrimp farms that decreases light penetration into water which in turn hinders photosynthesis and causes lower dissolved oxygen that are likely to increase shrimp mortality [58]. Mangroves are significant for protecting the coast against erosion [25], and they stabilize shorelines by reducing the height and energy of waves [88,89]. Mangroves also alter the turbidity of ambient waters through sediment trapping due to their position at the sea-land interface [63,64]. Riverine mangrove forests are likely to be more important for sediment trapping than fringe and basin forests [90].

[6] El Niño is the warm phase of the El Niño Southern Oscillation (also called ENSO), refers to the cycle of warm temperatures that occurs across the tropical Pacific Ocean. It is characterized by prolonged warming in the Pacific Ocean sea surface temperatures.

5.5. Salinity

Salinity is an increasing problem for coastal aquaculture. Cyclones with tidal surges and sea-level rise are likely to play a critical role in increasing salinity of shrimp farms. Cyclones push fully saline seawater from the deepwater layers onto the shelf and then to coastal areas [91]. Increased water salinity has reduced the availability of aquatic flora and fauna in aquaculture farms [59]. Coastal ecosystems are becoming increasingly threatened by loss of aquatic biodiversity which plays an important role in maintaining ecosystem services and resilience to climate change [92]. Mangroves prevent the entry of saltwater to inland areas, and thus, protect groundwater salinity [76]. Mangroves are known for their unique structural and functional adaptations to cope with salinity and also have mechanisms to actively remove salinity by salt extracting leaves [45].

5.6. Sea-level rise

Coastal aquaculture is vulnerable to sea-level rise due to global warming and glacier melting. Global sea-level appears to be rising by 2–3 mm each year [93], and it is predicted that global sea-level could rise 1 m by 2100 [94]. Sea-level rise affects coastal aquaculture as complete drying of shrimp farms may not be possible due to sea-level rise. Failure to dry shrimp farms results in increase toxicity level and pathogenic bacteria that affect shrimp, and making them more susceptible to disease [95]. Mangroves facilitate coastal adaptation to sea-level rise [61]. Mangroves enhance sediment accretion which in turn increases plant growth and production, and mitigates the impacts of sea-level rise on coastlines [25,47]. Mangroves may provide support for enhancing sea defences [96]. Restoration of mangroves is part of the adaptive response to sea-level rise in the Pacific Islands region [84]. Protection and rehabilitation of mangroves is also a priority adaptation strategy to sea-level rise for Martinique's coastal zone in the West Indies [97].

5.7. Sea-surface temperature

Global warming and the greenhouse effect lead to higher sea surface temperatures [91]. Thus, the coastal region will heat up faster as there is a greater contrast between the land and the sea [80]. Increased water temperature in coastal aquaculture farms may reduce dissolved oxygen level and increase toxicity of shrimp farms that could affect ecosystem functions [59]. Increased sea surface temperature affects the availability of wild prawn postlarvae because of shift in breeding season and reduce spawning rate [98]. Seasonal increase in water temperatures often causes death of prawn postlarvae and adult prawn [59]. The occurrence of shrimp diseases has been linked to fluctuations in temperature and salinity [99,100]. Mangroves play a key role in maintaining water temperature due to biofiltration, salt absorption, sediment trapping, and reducing saltwater intrusion into coastal areas [61,64].

6. REDD+: mangrove restoration for adaptation to climate change

Considering extreme vulnerability to the effects of climate change on coastal aquaculture and wider coastal economies and societies, adaptation strategies are needed. Mangrove restoration can be part of a broader approach to facilitating adaptation to climate change [61]. REDD+ can address the increased risks from coastal flooding, cyclones, and sea-level rise [25,28]. Mangrove

Table 3
Potential for sequestering blue carbon by restoration of mangrove forests through REDD+.

Mangrove area lost to coastal aquaculture[a] (million ha)	Restoration of mangrove area (%) through REDD+	Restoration of mangrove area (million ha) through REDD+	Carbon sequestration rate[b] (t/ha/yr)	Total carbon sequestration (million t/yr)
	10	0.19		0.22–0.26
	20	0.38		0.44–0.53
1.89	30	0.57	1.15–1.39	0.66–0.79
	40	0.76		0.87–1.06
	50	0.95		1.09–1.32

[a] Source: Valiela et al. [44].
[b] Source: Nellemann et al. [53] and Bouillon et al. [102].

reforestation and aforestation[7] facilitated by the REDD+ initiatives has the potential for conservation of mangrove forests [101]. REDD+ could act as an opportunity for restoring mangrove forests to compensate mangrove area lost by aquaculture with positive social and economic feedbacks, including for the aquaculture sector itself.

Mangrove restoration is a low-cost option for reducing blue carbon emissions [18,55]. There is growing interest in implementing REDD+ to protect mangrove forests for carbon offsets [24,56]. Mangrove restoration could help to sequester blue carbon. Global annual blue carbon sequestration rate is about 53 million tons, of which 16 million tons (30%) by mangroves [55]. Mangrove forests sequester blue carbon at the rate of 1.15–1.39 t/ha annually [53,102]. If REDD+ rehabilitated 10% of deforested mangrove areas by aquaculture, globally 0.22–0.26 million tons of blue carbon could be sequestered annually. Similarly, if REDD+ rehabilitated half of deforested mangrove areas by aquaculture, globally 1.09–1.32 million tons of blue carbon could be sequestered annually (Table 3).

Although REDD+ projects worldwide mainly concentrated on terrestrial forests, a number of REDD+ projects have recently focused on mangroves. For example, REDD+ projects in Asia have planned to include mangrove restoration for carbon offsets [103]. The aim of REDD+ project in Thailand is to conserve mangroves as an alternative to shrimp farming [104]. REDD+ strategies for the conservation of the Amazon basin have been developed [105,106]. REDD+ addresses carbon pools and ecosystem services of mangroves in Central Africa [107]. In Fiji, the mangrove ecosystems for climate change adaptation project aims to increase resilience through the REDD+ readiness process [30].

Restoration of mangrove forests through REDD+ would help ecosystem functions, including competition, decomposition, photosynthesis, predation, respiration, and water purification [108,109]. REDD+ can improve ecosystem services of mangrove forests, including biodiversity conservation, nutrient cycling, pest control, pollination, production, and water quality improvement [38,110]. Mangrove restoration through REDD+ is significant for sustainable coastal aquaculture to provide socioeconomic benefits among farming communities (Fig. 3). In order to get wider benefits from mangrove ecosystems, including food security, income, sustainable livelihoods, and poverty alleviation in coastal communities, attention must be given for the conservation of mangrove forests [111]. An increased awareness of the value of mangrove ecosystems has to be developed among coastal communities to generate a more solid basis for mangrove conservation [12].

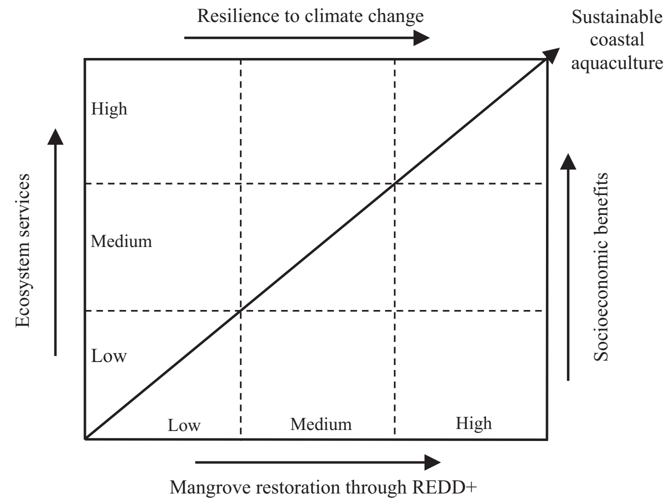

Fig. 3. A conceptual framework for sustainable coastal aquaculture by mangrove restoration through REDD+ with enhance resilience to climate change, ecosystem services, and socioeconomic benefits.

Involving local communities is significant for the conservation of mangrove forests for a clear understanding of local incentives [45,112,113].

Mangrove restoration through REDD+ can be effectively linked with sustainable coastal aquaculture practices. Coastal aquaculture can be managed so that the ecological functions of mangroves are not affected. Small-scale cage culture in mangroves can be practiced with less environmental impacts. Silviculture[8] may be practiced as an integral part of aquaculture for mangrove management [10,114]. The translocation of shrimp farming from deforested mangrove areas to onshore or near-shore can help to restore mangrove forests. Shrimp culture with finfish, shellfish, and seaweeds in "integrated multi-trophic aquaculture" can be an option to shift shrimp farming for improving its sustainability in the social, economic, and ecological aspects.

7. Conclusions

Globally, coastal aquaculture including shrimp farming has devastating effects on mangrove forests. At the same time, mangroves are the most carbon-rich forests in the tropics, and thus, ecologically and economically significant at the planetary level. The loss of mangroves through coastal aquaculture causes carbon emission and reduces carbon sequestration. Blue carbon emissions are being significantly enhanced due to devastating effects of shrimp culture on mangroves. The loss of mangroves by contemporary shrimp culture also has adverse impacts on ecosystem services. Because of mangrove deforestation and degradation, different climatic variables including coastal flooding, cyclone, drought, rainfall, salinity, sea-level rise, and sea surface temperature also have dramatic rebound effects on coastal aquaculture.

Mangrove restoration is considered part of adaptation to climate change. Mangrove restoration through REDD+ can address the increased risks from climate change. REDD+ is potentially a low-cost contribution to climate change mitigation that can play a significant role in reducing blue carbon emissions. There is growing interest in implementing REDD+ to protect mangrove forests for carbon offsets. REDD+ can help to restore mangrove

[7] "Reforestation" means planting of forests on lands that was previously contained forests but that has been converted to other land use practices, while "aforestation" means planting of new forests on lands that have not previously supported forests.

[8] Silviculture means the care and cultivation of forest trees. Silviculture is the art and science of controlling the composition, establishment, growth, health, and quality of forests to meet the multitude of purposes and values of society on a sustainable basis.

forests which in turn help to sequester carbon. REDD+ could act as an opportunity for restoring mangrove forests to compensate mangrove losses by coastal aquaculture. REDD+ provides a great, hitherto underutilized opportunity for the conservation of mangrove biodiversity and ecosystem services.

In order to realize the potential of synergistically linking the restoration of mangrove forests and coastal aquaculture through implementing REDD+, technical and financial assistance as well as institutional support are needed. In order to get wider benefits from mangrove restoration, all major stakeholders including international agencies, researchers, government and non-governmental organizations, and coastal communities should work together for the implementation of REDD+. This requires funding to establish effective collective learning platforms [115]. Green payments may be required for reducing blue carbon emissions by conservation of mangrove forests through REDD+ [24,54]. In order to increase the participation of coastal communities in REDD+, their awareness of the social, economic, and ecological functions will have to be addressed. Cultural issues within the coastal communities and rights to the benefits from mangrove restoration may have to be addressed to implement REDD+. Community based adaptation strategies which understand local priorities, vulnerabilities, and coping strategies in the face of environmentally-based livelihood stress may be needed to implement REDD+ for the restoration of mangrove forests [116]. Further research is also needed to implement REDD+ in respect to mangrove restoration, blue carbon sequestrations, and coastal aquaculture production.

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