Integrated mangrove-shrimp cultivation: Potential for blue carbon sequestration

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Abstract Globally, shrimp farming has had devastating effects on mangrove forests. However, mangroves are the most carbon-rich forests, with blue carbon (i.e., carbon in coastal and marine ecosystems) emissions seriously augmented due to devastating effects on mangrove forests. Nevertheless, integrated mangrove-shrimp cultivation has emerged as a part of the potential solution to blue carbon emissions. Integrated mangrove-shrimp farming is also known as organic aquaculture if deforested mangrove area does not exceed 50% of the total farm area. Mangrove destruction is not permitted in organic aquaculture and the former mangrove area in parts of the shrimp farm shall be reforested to at least 50% during a period of maximum 5 years according to Naturland organic aquaculture standards. This article reviews integrated mangrove-shrimp cultivation that can help to sequester blue carbon through mangrove restoration, which can be an option for climate change mitigation. However, the adoption of integrated mangrove-shrimp cultivation could face several challenges that need to be addressed in order to realize substantial benefits from blue carbon sequestration.

Keywords Adaptation · Blue carbon · Climate change · Mangroves · Organic aquaculture · Shrimp

INTRODUCTION

Globally, shrimp¹ farming expanded rapidly in the 1980s and 1990s, mostly in the tropical and subtropical regions of Asia and South America, driven by growing international demand and a high market price (Lebel et al. 2002; Primavera 2006; FAO 2007). Shrimp is primarily produced in developing countries for international trade. After being the most traded product in fish for decades, shrimp now ranks

second after salmon (FAO 2016). Despite economic benefits, globally shrimp farming has been under intense criticism because of its environmental and social impacts. These debates and arguments concern the impacts of shrimp farming on the ecosystem, biodiversity, and society (Pàez-Osuna 2001; Lebel et al. 2002; Bush et al. 2010).

Unplanned and unregulated shrimp farming has had devastating effects on mangrove forests. Rapid loss of mangroves across the world has accelerated over the last few decades, and coastal aquaculture including shrimp farming is one of the key reasons (Primavera 2006; Hamilton 2013; Richards and Friess 2016; Thomas et al. 2017). The rapid development 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 (FAO 2007; UNEP 2014). The loss of mangroves threatens ecosystem goods and services as mangroves are ecologically and economically important forests (Spalding et al. 2010; Alongi 2014). Mangroves provide a wide range of ecosystem goods and services, including biodiversity conservation, climate regulation, coastal protection, fisheries production, fuel, medicine, nutrient cycling, timber, and tourism (FAO 2007; UNEP 2014).

Although mangrove deforestation has been controlled in a number of countries, including Bangladesh, Fiji, Nigeria, and Venezuela (FAO 2007; Hamilton and Casey 2016), effluents from intensive shrimp farms continue to affect adjacent mangroves (Stokstad 2010; Bui et al. 2014). In

¹ Shrimps constitute a large group of crustaceans and they are widely distributed in marine and brackish water habitats. Most common shrimp aquaculture species are *Penaeus monodon*, *P. indicus*, *P. japonicus*, and *P. merguensis*.

recent years, many shrimp producing countries have experienced disease outbreaks due to environmental degradation as a result of mangrove deforestation with intensive shrimp cultivation (FAO 2016; Malik et al. 2017). Because of shrimp disease, many aquaculture farms are abandoned (Primavera 2006; Bournazel et al. 2015). Shrimp farming has also been accompanied by recent concerns over climate change due to mangrove deforestation (Ahmed and Glaser 2016).

Mangroves are the most carbon-rich forests in the tropics (Donato et al. 2011; Pendleton et al. 2012; Siikamäki et al. 2012; Alongi 2014). On average, mangroves store 3–4 times more carbon than tropical upland forests (Donato et al. 2011). However, globally mangrove deforestation rates are significantly higher than the average rates of global forest loss (Hamilton and Casey 2016; Richards and Friess 2016; Thomas et al. 2017). Blue carbon² emissions have been seriously increased by the loss of mangrove forests (Pendleton et al. 2012; Alongi 2014; Kauffman et al. 2014). Blue carbon is the carbon stored, sequestered,³ and released from coastal and marine ecosystems, including mangroves, salt marshes, and seagrasses (Nellemann et al. 2009; Siikamäki et al. 2012). Carbon emissions⁴ with other greenhouse gases (CH₄, N₂O) have been recognized as the dominant cause of climate change (IPCC 2014). It is, therefore, crucial to reduce blue carbon emissions from mangrove deforestation by shrimp cultivation to tackle anthropogenic⁵ climate change.

Preventing mangrove loss and the conservation of mangrove forests can help to reduce blue carbon emissions for climate change mitigation (McLeod et al. 2011; Pendleton et al. 2012; Siikamäki et al. 2012; Duarte et al. 2013; Murdiyarso et al. 2015). Globally, integrated mangrove-shrimp cultivation has emerged as a part of the potential solution to environmental problems (e.g., biotic depletion, eutrophication, soil and water salinization, and water pollution) faced by shrimp aquaculture (Primavera et al. 2000; Pàez-Osuna 2001; Ha et al. 2012a). Integrated mangrove-shrimp cultivation can help to reduce blue carbon emissions through mangrove restoration, which in turn sequesters blue carbon. The aim of this article is to

highlight the potentiality of blue carbon sequestration through integrated mangrove-shrimp cultivation.

MANGROVE DEFORESTATION AND BLUE CARBON EMISSIONS

Mangrove deforestation by shrimp cultivation

Mangroves occur in 118 countries worldwide, mainly on tropical and subtropical coastlines (Giri et al. 2011). Considerable variation of global mangrove area was found, for example, in 2000 global mangrove area was 15.74 million ha by FAO (2007), 15.23 million ha by Spalding et al. (2010), and 13.77 million ha by Giri et al. (2011). In a recent study by Hamilton and Casey (2016), total global mangrove area is 16.39 million ha in 2014, of which almost 50% is found in the top four countries: Indonesia, Brazil, Malaysia, and Papua New Guinea. The top 20 mangrove-holding countries contain 80–85% of global mangrove forests (Hamilton and Casey 2016). Southeast Asia contains 33.8% of the global mangrove forests (Thomas et al. 2017), while South Asia represents 7% of the global total (Giri et al. 2015).

Mangrove forests are one of the world's most threatened tropical ecosystems (Valiela et al. 2001; Duke et al. 2007). Globally, mangroves have declined by 30–50% over the past half century (FAO 2007; Donato et al. 2011). The annual deforestation rates of global mangroves are 1–3% (McLeod et al. 2011; Pendleton et al. 2012). It is predicted that all global mangrove forests could be lost in the next 100 years (Duke et al. 2007). Global mangrove deforestation continues at a much reduced rate of 0.16–0.39% per annum during 2000–2012 (Hamilton and Casey 2016). Mangrove forests were lost in Southeast Asia at an average rate of 0.18% per year during the period 2000–2012, which is lower than previous estimates of 1% per year (Richards and Friess 2016).

Over 3.6 million ha of global mangrove forests (20% of total mangrove area) have been lost since 1980 due to agriculture, aquaculture, overexploitation, tourism, and urbanization (Valiela et al. 2001; FAO 2007). Among deforested mangroves, 1.89 million ha (52%) were lost to coastal aquaculture, of which 1.4 million ha is attributed to shrimp culture and 0.49 million ha to other forms of aquaculture. The great majority of mangrove loss (1.69 million ha) is in Asia with shrimp farming accounting for 1.2 million ha of mangrove deforestation (Valiela et al. 2001). Indonesia has the highest mangrove deforestation rate (52 000 ha year⁻¹) among shrimp producing countries during the period 1980–2005, with a total loss of 40% of its mangroves (FAO 2007; Murdiyarso et al. 2015). In a study of eight countries (Bangladesh, Brazil, China, Ecuador,

² The *colors* of carbon are fossil fuels “brown carbon,” dust particles “black carbon,” terrestrial ecosystems “green carbon,” and coastal and marine ecosystems “blue carbon” (Nellemann et al. 2009).

³ Carbon sequestration is the process of increasing the carbon content of a reservoir other than the atmosphere. Sequestration is the removal of atmospheric CO₂ through biological (photosynthesis) or geological (storages in underground reservoirs) processes.

⁴ Carbon emission is the release of carbon into the atmosphere, which is attached to O₂ and becomes CO₂. One ton of carbon becomes 3.67 tons of CO₂ in the atmosphere.

⁵ Anthropogenic climate change refers to the production of greenhouse gases emitted by human activity.

Table 1 Global loss of mangrove forests and blue carbon stock by shrimp cultivation

Element	Statistics	Reference
Global mangrove forests in 2014 (million ha)	16.39	Hamilton and Casey (2016)
Global mangrove deforestation by shrimp cultivation during 1980–2000 (million ha)	1.4	Valiela et al. (2001)
Mangrove loss due to shrimp farming with other reasons in South Asia during 2000–2012 (million ha)	0.09	Giri et al. (2015)
Mangrove loss due to shrimp farming with other reasons in Latin America and the Caribbean during 2001–2010 (million ha)	0.05	Aide et al. (2013)
Mangrove deforestation by shrimp cultivation in Southeast Asia during 2000–2012 (million ha)	0.03	Richards and Friess (2016)
Approximately total global mangrove deforestation by shrimp cultivation since 1980 (million ha) ^a	1.5	This study
Blue carbon loss from conversion of mangroves to shrimp farms (t ha ⁻¹)	554	Kauffman et al. (2017)
Total loss of blue carbon from 1.5 million ha deforested mangroves to shrimp farms (million t)	831	This study

^a Mangrove deforestation by other reasons (excluding shrimp farming) in South Asia, Latin America, and the Caribbean were deducted from this calculation

India, Indonesia, Thailand, and Vietnam), aquaculture accounted for as much as 54% of total mangrove loss during the 1980s–1990s (Hamilton 2013). Over 100 000 ha of mangroves were lost during the period 2000–2012 in Southeast Asia, with aquaculture accounting for 30% (i.e., 30 000 ha) of the total loss (Richards and Friess 2016). In South Asia, 92 135 ha of mangroves were deforested during 2000–2012 due to shrimp farming with other reasons, while 80 461 ha were reforested with a net loss of 11 673 ha (Giri et al. 2015). Similarly, 54 600 ha of mangroves were lost in Latin America and the Caribbean during 2001–2010 due to shrimp farming with other reasons, while 32 800 ha were reforested with a net loss of 21 800 ha (Aide et al. 2013). It seems that approximately 1.5 million ha of global mangrove forests have been lost since 1980 due to shrimp cultivation (Table 1).

Blue carbon emissions

Global coverage of blue carbon ecosystems is about 51 million ha of which 63% is seagrasses, 27% is mangroves, and 10% is salt marshes. Globally, blue carbon ecosystems store about 11.5 billion t of carbon, of which the highest blue carbon pool (6.5 billion t) is mangroves (Siikamäki et al. 2012). On average, mangroves store 858 t ha⁻¹ of

blue carbon in their biomass and under soil (Kauffman et al. 2017). Mangroves store carbon in soils, living biomass above- and below-ground, and non-living biomass (McLeod et al. 2011; Kauffman et al. 2014). Mangroves have the greatest aboveground biomass as they can grow up to 40 m height (Spalding et al. 2010). However, over 80% of the mangrove's blue carbon stock is in the soils. Globally, mangrove soils contain about 5 billion t of blue carbon within 1 m soil depth (Jardine and Siikamäki 2014).

Blue carbon emissions from mangrove deforestation due to shrimp cultivation are accumulating (Pendleton et al. 2012; Kauffman et al. 2017). Globally, the blue carbon emission rate is 58.7 million t annually, of which 33.5 million t (57%) derives from mangrove losses (Siikamäki et al. 2012). Cutting down mangroves to create shrimp farms releases significant amounts of blue carbon and depletes storage facilities. Blue carbon stocks of abandoned shrimp ponds are only ~11% that of mangroves (Kauffman et al. 2014). The aboveground carbon stock in shrimp ponds is 91% less than undisturbed mangrove forests. On average, the potential loss of blue carbon from the conversion of mangroves to shrimp farms is 554 t ha⁻¹ (Kauffman et al. 2017). At this rate, the global loss of blue carbon stock from 1.5 million ha of deforested mangroves to shrimp farms is about 831 million t (Table 1).

There is a carbon footprint of 437 kg for every kilogram of shrimp produced on deforested mangroves (Kauffman et al. 2017). The emissions from 1 ha of mangrove forest converted to shrimp farm are equivalent to the emissions of 5 ha of tropical evergreen forest conversion and 11.5 ha of tropical dry forest conversion (Kauffman et al. 2014). The potential blue carbon emissions due to the degradation of aboveground biomass in the Indian Sundarban mangroves over the last four decades were 427 242 t, equivalent to US\$64.29 million (Akhand et al. 2017). The conversion of mangroves to shrimp ponds in Puttalam Lagoon, Sri Lanka, led to a total loss of 191 584 t carbon between 1990 and 2012, making up 75.5% of the total carbon loss (Bournazel et al. 2015). About 80% of the living carbon lost (7.01 million t) in Ecuadorian mangrove forests can be attributed to direct displacement of mangroves by shrimp cultivation (Hamilton and Lovette 2015).

Linking blue carbon emissions and climate change

Blue carbon plays a crucial role in regulating our climate (Nellemann et al. 2009; Siikamäki et al. 2012). Global CO₂ concentration in the atmosphere would be much higher than it is without the contribution of coastal ecosystems to global biological carbon sequestration (Trummer et al. 2009). However, global coastal ecosystems including mangrove forests are among the most rapidly disappearing

natural ecosystems. One-third of the world's coastal ecosystems have already been lost over recent decades (McLeod et al. 2011). The estimated annual loss of coastal ecosystems is $\sim 8000 \text{ km}^2$ (Waycott et al. 2009; Spalding et al. 2010; Pendleton et al. 2012). Blue carbon emissions due to devastating effects on coastal ecosystems including mangrove forests can accelerate climate change. Further conversion of mangroves to shrimp farms could increase blue carbon emissions. High blue carbon emissions by the expansion of shrimp cultivation could augment climate change (Kauffman et al. 2014; Ahmed and Glaser 2016).

Climate change with mangrove deforestation also has adverse effects on shrimp cultivation. The impacts of climate change on shrimp production have been associated with different climatic variables, including coastal flooding, cyclones, rainfall variation, saltwater intrusion, sea level rise, and sea surface temperature (Ahmed and Diana 2015). Shrimp are highly sensitive to ecological conditions, and changes in the ecosystem of shrimp farms due to climatic variables have profound effects on their survival, growth, and production (Ahmed and Glaser 2016). Moreover, mangrove deforestation makes shrimp farming communities more vulnerable to climate change as over 100 million people live within 10 km of significant mangrove areas (UNEP 2014). Coastal communities in India located behind deforested mangroves are subject to more damage from super cyclone and tsunami (Kathiresan and Rajendran 2005; Das and Vincent 2009).

INTEGRATED MANGROVE-SHRIMP CULTIVATION

Silvoaquaculture or silvofisheries

Integrated mangrove-shrimp cultivation is commonly known as silvoaquaculture or silvofisheries, which has been recognized as environmentally friendly aquaculture (Primavera et al. 2000; Ha et al. 2012a; Bosma et al. 2016). To compensate for mangrove deforestation by shrimp cultivation, one of the adaptation strategies devised in Southeast Asian countries is to develop silvofisheries for the conservation, rehabilitation, and utilization of mangroves (Primavera et al. 2000). Mangrove friendly aquaculture is amenable to small-scale farmers and can be adopted in mangrove conservation (Primavera 2006). Integrated mangrove-shrimp farming is a form of low-input sustainable aquaculture (Fitzgerald 2000). Favorable biophysical conditions of mangrove forests could be utilized for integrated mangrove-shrimp cultivation (Fig. 1). Since 1978, integrated mangrove-shrimp culture has been practiced in Indonesia and Vietnam (Sukardjo 1989; Hai 2005).

Silvofisheries were initially developed in Myanmar about 70 years ago and subsequently introduced in Indonesia in 1978 by the Department of Forestry to cultivate shrimp and fish (e.g., milkfish, mullet, sea bass, and tilapia) with mangroves (Takashima 2000). In integrated mangrove-shrimp cultivation, the mangrove area ranges from 30 to 78% in Vietnam, depending on the size of cultivated land (Ha et al. 2012a; Jonell and Henriksson 2015). Integrated mangrove-shrimp farming has also been practiced in Malaysia, the Philippines, and Thailand (Primavera et al. 2000). This farming system has also been proposed in India (Oswin and Ali-Hussain 2001).

Three main types of mangrove-shrimp production systems can be found: (1) integrated: water canals between platforms planted with mangrove, mainly in Indonesia and Vietnam, (2) associated: large areas of water are intermixed with a large mangrove area, in Vietnam, and (3) separated: dyke separating water from mangrove, in the Philippines and South America (Bosma et al. 2016). Extensive and semi-intensive farming systems are usually followed in integrated mangrove-shrimp culture. Farmers stock shrimp and fish fry from wild through tidal water exchange and hatchery sources, but they do not apply feeds and hardly use chemicals as they depend on natural recruitment of shrimp (Primavera et al. 2000; Johnston et al. 2000a; Bosma et al. 2016). Suitable site selection, mangrove vegetation, species of mangrove trees, soil type, water quality, tidal water with inlet and outlet facilities, and mangrove ecosystems are also considered in this integrated farming (Takashima 2000). Moreover, land ownership, integrated coastal zone planning and development, resource utilization, better understanding of trophic production and food-web utilization, and economic return (high-value fish culture, increased production and reduced production costs, and marketing facilities) are important factors for sustainable integrated mangrove-shrimp cultivation (Fitzgerald 2000; Baumgartner and Nguyen 2017). In fact, integrated mangrove-shrimp farming is a complex social-ecological system (Bush et al. 2010), and thus, government management, land use policy, and regulation are needed for sustainable shrimp production that maintains the ecological function of mangroves (Ha et al. 2012a, 2014).

Organic shrimp farming

The integrated mangrove-shrimp farming system has been recognized as an organic aquaculture practice (Ha et al. 2012b; Bosma et al. 2016). Globally, organic aquaculture emerged as an alternative to help solve environmental problems and the health and safety issues faced by modern

Fig. 1 Favorable biophysical conditions of mangrove forests could be utilized for integrated mangrove-shrimp cultivation

aquaculture (Biao 2008). Organic aquaculture plays an important role in improving environmental conditions, often reducing production costs, and eco-friendly farming with positive social implications. General characteristics of organic aquaculture are no artificial chemicals, minimal environmental impacts, and ecosystem-based management (IFOAM EU Group 2010; IFOAM 2014). Environmental degradation is incompatible with the concept of organic aquaculture. The construction of shrimp farms should be environmentally friendly in terms of efficient management of landscape and biophysical resources. Maintaining biodiversity and local ecosystems are also key principles in organic aquaculture (Naturland 2016). Integrated mangrove-shrimp cultivation could help prevent shrimp disease as organic management practices achieve a higher level of disease resistance in shrimp due to low off-farm inputs to maintain and enhance farming ecosystems (IFOAM 2014; Naturland 2016).

Organic shrimp culture with the integration of mangroves sets high performance standards that safeguard the

environment. According to Naturland⁶ standards, organic aquaculture does not allow the removal or damage to mangroves for construction and expansion of shrimp farms. However, shrimp farms, which in part cover a former mangrove area, can be converted to organic culture, if deforested mangrove area does not exceed 50% of the total farm area. The former mangrove area in parts of the shrimp farm shall be reforested to at least 50% during a period of maximum 5 years. Shrimp harvest from this farm is not permitted to be labeled and marketed as an organic product until successful completion of reforestation. Additionally, the annual progress in reforestation activities as mentioned in the conversion plan shall be confirmed by the certification committee

⁶ Naturland is a renowned organic certifying agency of Germany that initiated the first international organic aquaculture project. In 1995, the first international organic aquaculture project aimed at developing a standard for organic salmon culture was launched in Ireland with the help of the Naturland Association, based on principles of the International Federation of Organic Agriculture Movements (IFOAM) and the European organic regulations (IFOAM EU Group 2010).

Table 2 Rehabilitation of mangroves through organic shrimp cultivation

Feature	System response by organic aquaculture
Mangrove deforestation or destruction	Not allowed
Former mangrove area to shrimp farms	Can be allowed, if deforested mangroves do not exceed 50% of the total farm area
If deforested mangroves exceed 50% of the total farm area	Mangroves should be reforested at least 50% of the total farm area within 5 years
Successful completion of reforestation over 50% of the total farm area	Confirmation by certification committee required
If 1.5 million ha of global deforested mangroves to shrimp farms converted to organic aquaculture	It could rehabilitate 50% (0.75 million ha) of deforested mangroves

Source Adapted from Naturland (2016)

(Naturland 2016). The main difference between organic and non-organic farming is the share of mangroves, with certified organic farms generally occupying a larger share of mangrove (50–78%) in the ponds than for non-organic farms (Jonell and Henriksson 2015). As per Naturland standards, if 1.5 million ha of global deforested mangroves to shrimp farms were converted to organic aquaculture, it would rehabilitate 50% (0.75 million ha) of mangrove forests (Table 2). Organic shrimp cultivation with the integration of mangroves has been practiced in Ca Mau Province, Vietnam, to create an organic coast (Ha et al. 2012b).

However, organic aquaculture often faces challenges in certification, which are costly and present an obstacle to the organic market (Biao 2008; Ha et al. 2012b). Government support, key stakeholder involvement, and private sector investment are needed to improve certification for access to the organic market. There is a growing demand for organic food in the global market, and certain consumers are willing to pay 15–30% more for organic products (Ruangpan 2007; Aschemann-Witzel and Zielke 2017). Organic shrimp farming households would greatly benefit from higher market price, which will motivate more farmers to engage in organic shrimp production in Bangladesh and Vietnam (Paul and Vogl 2013; Baumgartner and Nguyen 2017).

Productivity

The annual productivity of shrimp varies greatly in integrated mangrove-shrimp farming, ranging from 175 to 398 kg ha⁻¹ of water area (Table 3). Higher shrimp yield was found in certified organic farms (360 kg ha⁻¹) than non-organic farms (229 kg ha⁻¹) (Jonell and Henriksson

Table 3 Key features with productivity of integrated mangrove-shrimp farming

Feature	Information	Reference
Mangrove cover (%)	30–78	Ha et al. (2012a); Jonell and Henriksson (2015)
Farming systems	Extensive, semi-intensive	Bunting et al. (2013)
Farm size or pond area (ha)	1–3	Ha et al. (2012a, 2014)
Culture period (months)	4–6	Hai (2005); Bunting et al. (2013)
Shrimp productivity (kg ha ⁻¹ year ⁻¹)	175–398	Binh et al. (1997); Minh et al. (2001); Ha et al. (2012a); Jonell and Henriksson (2015); Bosma et al. (2016)

2015). Including fish, the annual productivity varies from 703 to 811 kg ha⁻¹ (Takashima 2000). Shrimp yield is affected by farm management, pond size, availability of natural feed (benthos, periphyton, plankton), water quality (dissolved oxygen, pH, transparency), and weather conditions (sunlight, rainfall) (Fitzgerald 2000; Johnston et al. 2000b; Takashima 2000). A number of factors of the mangrove also affect shrimp production, including species of mangrove, age of the trees, density of trees (the number of trees per m²), and farm area covered by forest (Binh et al. 1997; Hai 2005; Bosma et al. 2016). Better management practices and sustainable intensification⁷ could increase shrimp productivity in integrated mangrove-shrimp aquaculture (Bunting et al. 2013).

In addition to physical production, socioeconomic and environmental productivity can be distinguished in integrated mangrove-shrimp farming. Shrimp production with the integration of mangroves is economically viable due to achieving considerable profit (Bunting et al. 2013). Integrated mangrove-shrimp culture requires low investment and provides livelihood diversification with regular income for coastal people (Bosma et al. 2016). Shrimp farming households with the integration of mangroves are able to maximize income (Ha et al. 2014). The integrated mangrove-shrimp model in Vietnam is a sustainable system, which is considered as the best practice for increasing income of farming households with sustainable livelihood through mangrove conservation (Ha et al. 2012a). Integrated mangrove-shrimp farming could help to fulfill the promises of food security and poverty alleviation without adverse socioeconomic and environmental effects (Primavera 2006). In fact, shrimp culture with the integration of mangroves provides a wide range of ecosystem services.

⁷ Sustainable intensification produces more food from the same area of land and water while reducing negative environmental impacts.

Table 4 Potential for sequestering blue carbon by restoration of mangroves through integrated/organic shrimp cultivation

Global mangrove area lost to shrimp culture (million ha)	Restoration of mangrove area (%) through integrated/organic shrimp culture	Restoration of mangrove area (million ha) through integrated/organic shrimp culture	Carbon sequestration rate ($\text{t ha}^{-1} \text{ year}^{-1}$) ^a	Total carbon sequestration (million t year^{-1})
1.5	10	0.15	1.15–1.39	0.17–0.21
	20	0.30		0.35–0.42
	30	0.45		0.52–0.63
	40	0.60		0.69–0.83
	50	0.75		0.86–1.04

^a Source Bouillon et al. (2008); Nellemann et al. (2009); Siikamäki et al. (2012)

The annual economic value of mangrove ecosystem services has been estimated at US\$10 158–12 392 ha^{-1} in Thailand (Barbier 2007).

MANGROVE RESTORATION AND BLUE CARBON SEQUESTRATION

Integrated mangrove-shrimp cultivation is one of the options for mangrove restoration,⁸ which could reduce blue carbon emissions. Mangrove restoration could play a significant role in mitigating climate change by sequestering and storing blue carbon (Bouillon et al. 2008; Donato et al. 2011; Irving et al. 2011; Mcleod et al. 2011; Pendleton et al. 2012). Blue carbon could be seen as an opportunity for restoration and conservation of mangroves to promote ecosystem-based approaches for adaptation and mitigation to climate change (Pidgeon et al. 2015). Mangrove restoration through integrated mangrove-shrimp cultivation is therefore a significant climate change adaption and mitigation action. In order to capture and store carbon for climate change mitigation, mangrove reforestation surrounding shrimp farms are suggested in Vietnam (Bui et al. 2014). Rehabilitating mangroves in abandoned shrimp ponds of Panay Island, the Philippines could help climate change mitigation and adaptation (Duncan et al. 2016).

Globally, the blue carbon sequestration rate is about 53 million t annually, of which 16 million t (30%) is by mangroves (Siikamäki et al. 2012). If integrated or organic shrimp culture rehabilitates 10% (0.15 million ha) of the deforested mangrove area globally, it could sequester 0.17–0.21 million t of blue carbon annually, as mangroves sequester blue carbon at a rate of 1.15–1.39 $\text{t ha}^{-1} \text{ year}^{-1}$ (Bouillon et al. 2008; Nellemann et al. 2009; Siikamäki et al. 2012), depending on a number of factors, including biotic influences, geomorphology, local climate and

environment, tidal amplitude, and vegetation type (Bouillon et al. 2008; Schile et al. 2017). Similarly, if integrated or organic shrimp culture rehabilitates 50% (0.75 million ha) of the deforested mangrove area globally, it could sequester 0.86–1.04 million t of blue carbon annually (Table 4). Thus, integrated mangrove-shrimp cultivation to sequester blue carbon has some climate change mitigation potential. Blue carbon sequestration is considered a cost-effective option to achieve positive climate change mitigation and adaptation outcomes (Thomas 2014). Blue carbon can be traded in a similar way to green carbon for climate change mitigation (Chevallier 2012). An average carbon sequestration value in Kenya was estimated to be US\$251 $\text{ha}^{-1} \text{ year}^{-1}$ (Huxham et al. 2015).

Blue carbon sequestration through mangrove restoration by integrated mangrove-shrimp cultivation could offer a wide range of ecosystem goods and services that support climate change adaptation and mitigation (Fig. 2). Mangrove restoration could increase resilience to climate change as mangroves are instrumental in protecting low-lying areas from coastal flooding, cyclones, saltwater intrusion, sea level rise, and shoreline erosion (Das and Vincent 2009; McIvor et al. 2012; Duarte et al. 2013). Mangroves are significant for resilience to climatic effects on shrimp cultivation (Ahmed and Glaser 2016). Nutrient outflow from shrimp farms can be mitigated by mangroves to maintain surrounding water quality through filtering nutrients (Satheeshkumar and Khan 2012; Gillis et al. 2014). Reducing nutrient loads in mangroves can maximize blue carbon sequestration (Macreadie et al. 2017). Maintaining mangrove ecosystems would increase ecosystem services that have a strong potential to increase resilience to climate change by sequestering carbon and reducing greenhouse gas emissions. In Vietnam, organic mangrove-shrimp farms have lower greenhouse gas emissions than non-certified farms due to differences in land management practices (Jonell and Henriksson 2015). In fact, organic aquaculture has a significant role in addressing climate change (Scialabba and Müller-Lindenlauf 2010; Criveanu and Sperdea 2014).

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.

Fig. 2 Linking shrimp cultivation, mangrove restoration, and blue carbon sequestration to provide a wide range of ecosystem goods and services that can help climate change adaptation and mitigation to coastal communities

Despite potential benefits from integrated mangrove-shrimp cultivation for adaptation to climate change, the implementation of large-scale mangrove-shrimp cultivation could face social, economic, and ecological challenges (Primavera et al. 2000; Ha et al. 2012b). Mangrove rehabilitation in abandoned fishponds of Panay Island, the Philippines, is often constrained by complexities in intertidal zone management and conflicts with current rehabilitation programs (Duncan et al. 2016). Forest allocation, land tenure conflicts, user rights, and conflict associated with access right distribution between farmers and forest companies are also important factors for the implementation of integrated mangrove-shrimp cultivation in Vietnam (Ha et al. 2014). This farming system will also face ecological and technological problems due to its operation in integrated conditions. Moreover, mangrove restoration through shrimp cultivation is complicated and challenging because of the effects of intensive human intervention with their poor socioeconomic conditions. Overall, mangrove ecology, local community, and economic support are major

factors for the successful restoration of mangroves (Biswas et al. 2009). Thus, ecological soundness, social acceptability, and economic viability of integrated mangrove-shrimp cultivation will need to be determined for its sustainable development.

Institutional support with technical and financial assistance is needed to overcome these challenges. The United Nations program on Reducing Emissions from Deforestation and forest Degradation (REDD+) has the potential for restoration of mangroves with the integration of shrimp culture (UNEP 2014). Key stakeholder involvement including government and Non-Governmental Organizations (NGOs), researchers, policymakers, and private sector investment are also needed for the successful implementation of integrated mangrove-shrimp cultivation. Community-based mangrove restoration may also raise awareness among local communities regarding benefits of conserving mangrove forests. Effective participation of indigenous peoples and local communities in forest management can support the conservation of mangroves (Roy

2016; Vierros 2017). In fact, Bangladesh, Malaysia, and Vietnam have shown success in mangrove restoration through sustainable management (FAO 2007).

CONCLUSIONS

Integrated mangrove-shrimp cultivation, also known as organic aquaculture, is an option for mangrove restoration to compensate for mangrove area lost through conventional shrimp aquaculture. Shrimp farming with the integration of mangroves is a promising mechanism to reduce blue carbon emissions. Moreover, integrated mangrove-shrimp cultivation can help to sequester blue carbon through mangrove restoration, which is a crucial aspect to mitigating climate change. However, the adoption of large-scale integrated mangrove-shrimp cultivation will face several social, economic, ecological, and technical challenges.

In order to realize the potential of synergistically linking integrated mangrove-shrimp cultivation to reduce blue carbon emissions and sequester blue carbon for climate change mitigation, technical and financial assistance with institutional support are needed. All key stakeholders including international agencies, researchers, policymakers, government agencies, NGOs, and coastal communities should work together to implement integrated mangrove-shrimp cultivation. Financial incentives to coastal communities may be required for reducing blue carbon emissions and maximizing sequestration by integrated mangrove-shrimp cultivation. In order to increase the participation of coastal communities in integrated mangrove-shrimp cultivation, their awareness of the social, economic, and ecological functions have to be addressed. Participation of coastal communities in mangrove restoration could be increased through raising their awareness by extension services, technical assistance, and training programs. Cultural issues within the coastal communities, including rights to the benefits from mangrove restoration may have to be addressed to facilitate the successful adoption of integrated mangrove-shrimp cultivation. Intensive research is also needed to understand the social, economic, and ecological processes to establish environmentally and socially beneficial integrated mangrove-shrimp cultivation, which succeeds in achieving significant blue carbon sequestration for adaptation to climate change.

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