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Determining synergies and trade-offs between adaptation, mitigation and development in coastal socio-ecological systems in Bangladesh

Ranjan Roy [a,*], Moynul Hasan Monju [a], Mou Leong Tan [b], Md. Sadique Rahman [c], Shilpi Kundu [a], Md. Shahinoor Rahman [d], Byomkesh Talukder [e], Md. Simul Bhuyan [f]

[a] Dept. of Agricultural Extension & Information System, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh
[b] Geography Section, School of Humanities, Universiti Sains Malaysia, 11800 Penang, Malaysia
[c] Dept. of Management and Finance, Sher-e-Bangla Agricultural University, Dhaka, Bangladesh
[d] Dept. of Earth and Environmental Sciences, New Jersey City University, NJ, USA
[e] Dahdaleh Institute for Global Health Research, York University, Ontario, Canada
[f] Bangladesh Oceanographic Research Institute, Cox's Bazar-4730, Bangladesh

A R T I C L E I N F O

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A B S T R A C T

Mapping synergies and trade-offs is crucial for managing climate change impacts on coastal socio-ecological systems (SESs) through integrated response. This study employed the DPSIR (drivers, pressures, states, impacts, and responses) framework, focus group discussions, and participatory workshops to determine synergies, and trade-offs and develop measures to maximize synergies and minimize trade-offs between adaptation, mitigation and development in five coastal SESs in Bangladesh. The findings indicated that climate-smart farming was a major intervention that facilitated synergies between agricultural production and climate adaptation and mitigation. The major trade-off identified was that between agricultural production and the overexploitation of marine and coastal resources. The findings also revealed that overall, synergies were more prevalent than trade-offs in the coastal SESs. Three broad measures (namely, government's financial, institutional and regulatory support) were devised for maximizing synergies and minimizing trade-offs depending mainly on the pace and magnitude of adopting climate-resilient and/or -smart approaches needed to attain multiple societal objectives simultaneously. Critical policy implications include developing innovative financial mechanisms, strengthening natural resources stewardship, investing in sustainable intensification of polder agriculture, and improving coastal institutional scaffolds for building climate-resilient coastal zones.

1. Introduction

Climate change causes complicated interactions between climate hazards, exposure and vulnerability across the globe. These interactions result in increased risks, especially in coastal zones where disastrous effects are more visible and escalating quickly (Nicholls et al., 2007; Wong et al., 2014). The South Asian region including Bangladesh has the world's most diversified ecosystems and climatic regimes (Ahmed et al., 2019). However, the frequency and intensity of climatic catastrophes on coastal socioecological systems (SESs)

* Corresponding author. Dept. of Agricultural Extension & Information System, Sher-e-Bangla Agricultural University, Dhaka 1207, Bangladesh.
E-mail address: ranjan@sau.edu.bd (R. Roy).

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have increased noticeably in recent decades, particularly in Bangladesh due to its limited adaptation capacity and ability (GED, 2018; Dastagir, 2015). The coastal populations in Bangladesh are particularly vulnerable to climatic (and non-climatic) hazards owing to a combination of socioeconomic factors such as high population density and poverty and geographical factors including flat, low-lying, and delta-exposed topography, as well as rising seas, recurrent floods and intensifying cyclones (Roy et al., 2019; Uddin et al., 2019; GED, 2018; Intergovernmental Panel on Climate Change, 2014, 2018; Ahmed, 2006).

In Bangladesh, the government has employed various adaptation, mitigation and development interventions as responses to sea level rise, increases in salinity, waterlogging and cyclones. These include cultivating stress-tolerant crop varieties and irrigation infrastructure development to reduce the risk of natural hazards (Hossain and Saha, 2019; Maya et al., 2019; Roy, 2018). While climate change adaptation is best thought of as a series of events unfolding in response to a variety of social and environmental forces at local, regional, national, international and planetary scales, climate change mitigation can be thought of as a proactive set of concrete actions to reduce and/or prevent anthropogenic greenhouse gas (GHG) emissions (Thornton and Manasfi, 2010). Adaptation and mitigation interventions help to address climate change, but no single option is sufficient by itself (Intergovernmental Panel on Climate Change, 2014). Integrated responses that link adaptation and mitigation with other societal objectives generate mutual benefits and introduce co-benefits with other development policies (Qi and Terton, 2022). These integrated responses are useful for addressing SESs due to their complex and adaptive nature (Bruley et al., 2021).

Although significant progress has been made in increasing agricultural production, growing income and reducing poverty in Bangladesh, current coastal development trajectories are leading away from climate-resilient development (GoB, 2021). This situation draws attention to the urgency of climate actions that reduce GHG emissions as well as the effective implementation of adaptation measures to address the impacts of the changing climate and build the resilience of the human and natural systems (Fuso Nerini et al., 2018; Haines et al., 2017; Xu and Ramanathan, 2017). Policy-makers must rethink the linkages between coastal development and climate actions to leverage synergies and tackle trade-offs among development interventions and policies as efforts to eradicate poverty and hunger, increase farming production and better livelihoods (collectively the UN's sustainable development goals) can contribute to worsening climate change (Fuso Nerini et al., 2018). Simultaneously, climate actions to meet the goals of the Nationally Determined Contributions (MoEFCC, 2021) as well as the Paris Agreement can weaken progress toward some SDGs (Hegre et al., 2020).

The existing literature on the synergies and trade-offs between sustainable development goals (e.g., Fuso Nerini et al., 2018; Denton et al., 2014) highlight the importance of devising mechanisms for capitalizing on potential synergies and managing trade-offs between coastal development, adaptation and mitigation. Synergies occur when one practice helps to achieve one goal and also assists to attain others. In contrast, trade-offs happen when a practice achieves one goal but undermines others. The complicated decision-making process in climate change management involves trade-offs and synergies as well as conflicts and co-benefits that differ based on the precise goals to be met (Qi and Terton 2022; Akinyi et al., 2021). Analysis of these synergies and trade-offs are therefore increasingly used in sustainable development to advance the understandings of policy interactions (Weitz et al., 2018), policy coherence (Qi and Terton 2022) and policy coordination (Langou et al., 2020). Isolated policy/development interventions result in lost opportunities to maximize synergies and have adverse effects including delayed impacts of policies. Impaired prioritization and sequencing actions result in less efficient or effective resource use as well as incoherent planning and development (Schipper et al., 2022; Qi and Terton 2022; Langou et al., 2020; Weitz et al., 2018; Mainali et al., 2018). Researchers have emphasized that trade-offs and synergies must be openly evaluated as part of an effective climate management process (Schipper et al., 2022; Denton et al., 2014). Addressing them early on is critical since the more trade-offs there are, the more complex the decision-making process becomes (Akinyi et al., 2021).

Previous studies explored synergies and trade-offs in various areas, including agriculture (Kassam et al., 2012), ecosystem-based conservation (Locatelli et al., 2015), agroforestry (Duguma et al., 2014) and climate policies (Shrestha and Dhakal, 2019). These studies have drawn useful conclusions about how to leverage synergies to devise win-win solutions in designing transformative policies (Laurikka, 2013) that will lead to low-carbon and resilient economic development (Behnassi et al., 2014). In Bangladesh, authorities such as the Ministry of Water Resources (MoWR) and Ministry of Agriculture (MoA) have superficially considered trade-offs and synergies in formulating key policy instruments such as the Master Plan for Coastal Agricultural Development (FAO, 2012), Coastal Development Strategy (MoWR, 2006) and Coastal Zone Policy (MoWR, 2005).

However, there is a dearth of comprehensive studies related to synergies and trade-offs between adaptation, mitigation and development in coastal SESs. Coastal SESs are composed of economic (e.g., agriculture, aquaculture and livestock), ecological (e.g., forest and vegetation), and social (human health and settlements) subsystems and their interactions (Refulio-Coronado et al., 2021; Leslie et al., 2015). To fill this gap, this study was conducted to determine synergies and trade-offs as well as to develop measures of maximizing synergies and minimizing trade-offs between adaptation, mitigation and development (i.e., productivity) in five coastal SESs: irrigated and rain-fed agriculture, saltwater shrimp production, freshwater prawn production and mangrove-dependent. The findings will assist policymakers in designing concrete steps to strengthen integrated climate strategies and catalyze action toward developing climate-resilient coastal zones.

2. Methodology

2.1. Study areas and data sources

This study was conducted in the coastal zone of Bangladesh since the coastal area is identified as an "agro-ecologically disadvantaged region" by the government of Bangladesh (http://www.warpo.gov.bd/). This area is witnessing substantial outmigration and an unpredictable demographic future (Ahmad, 2019). Coastal people are enduring food poverty and relying on agriculture/crops (40%), fisheries (20%), and forestry (25%) for their living (Hossain et al., 2015; Lazar et al., 2015). This zone covers 19 districts (administrative units) and 147 sub-districts that have proximity to the Bay of Bengal (Fig. 1).

This study was conducted in five of the 19 districts: Barishal, Noakhali, Khulna, Cox's Bazar and Satkhira in 2022 (Table 1). Five sub-districts were deliberately selected from these five districts, namely, Barisal Sadar, Hatiya, Dumuria, Cox's Bazar Sadar and Shyamnagar, representing five coastal SESs: irrigated agriculture, rain-fed agriculture, freshwater prawn production, saltwater shrimp production and mangrove-dependent, respectively. The selection of districts, sub-districts and SESs was based on personal communication with the local Agricultural Extension Offices (AEOs), previous literature review (e.g., Mallick, 2019; Adams et al., 2018), and various reports of the Bangladesh Bureau of Statistics (BBS), for instance, Bangladesh Disaster-Related Statistics: Climate Change and Natural Disaster Perspectives (BBS, 2016) and the Yearbook of Agricultural Statistics-2015 (BBS, 2016).

Many people have started saltwater shrimp production in Cox's Bazar Sadar sub-district (Cox's Bazar district), while in Dumuria sub-district (Khulna district), people have invested in freshwater prawn production. Between 2000 and 2017, the area under the freshwater prawn system in Dumuria has been expanded from 3,170 ha to 11,300 ha (Upazila Fisheries Office, 2017). In Hatiya sub-district (Noakhali district), farmers were largely dependent on rainfed agriculture, while farmers in Barishal Sadar sub-district (Barishal district) mainly relied on irrigated agriculture. Farmers in Shyamnagar sub-district (Satkhira district) were primarily dependent on mangrove ecosystems and their resources (BBS, 2016).

2.2. Research approach

Climate-resilient coastal planning is required not only to identify the synergies and trade-offs but also to devise mechanisms to maximize the synergies and minimize the trade-offs. To map and understand these phenomena, this study employed the DPSIR (drivers, pressures, states, impacts and responses) framework, focus group discussions and participatory workshops for data collection, analysis and drawing conclusions. The objectives were achieved by following these steps: (a) determining the synergies and trade-offs within these coastal SESs through exploring respondents' daily activities and identifying their strategies for coping and adapting by employing the DPSIR framework and conducting focus group discussions, (b) identifying significant synergies and trade-offs by conducting participatory workshops, and (c) determining measures to maximize synergies and minimize trade-offs by applying mixed methods: focus group discussions and workshops.

2.2.1. DPSIR framework

Comprehensive environmental accounting frameworks are desperately needed to address current and imminent challenges of the

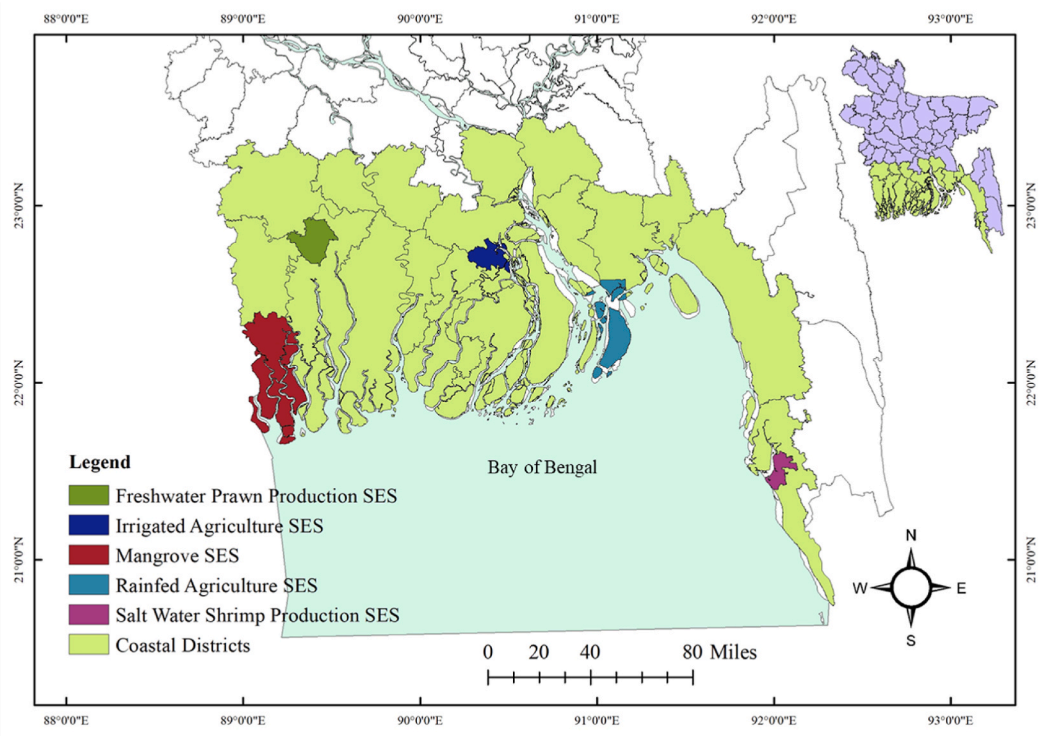

Fig. 1. Maps of the study sites. Top right: a map of Bangladesh with its administrative districts. Left side: a map of coastal zone with different colored 5 socioecological systems (and/or subdistricts) from where data were collected.

Table 1
Key characteristics of the coastal socioecological systems.

Attributes	Socioecological systems				
	Freshwater prawn production	Irrigated agriculture	Mangrove dependent	Rainfed agriculture	Saltwater shrimp production
Districts	Khulna	Barishal	Satkhira	Noakhali	Cox's Bazar
Sub-districts	Dumuria	Barishal Sadar	Shyamnagar	Hatia	Cox's Bazar Sadar
Population	305,675	547,259	318,254	452,463	459,082
Area (sq.km)	454.23	324.40	1968.00	1508.23	228.23
Literacy rate (%)	52.58	69.30	48.62	34.21	49.22
Key livelihood activities	• Aquaculture • Commerce • Service • Transport and communication • Nonagricultural labor	• Commerce • Service • Agriculture • Transport and communication • Construction	• Agriculture • Commerce • Nonagricultural labor • Service • Industry	• Agriculture • Commerce • Nonagricultural labor • Service • Transport and communication	• Aquaculture • Commerce • Service • Nonagricultural labor • Transport and communication
Key characteristics	• Characterized by Ganges tidal floodplain AEZ • Occupies unstable alluvial land within and adjoining the Ganges River • Main crops: paddy, jute, vegetables • Main exports: paddy, rice, betel nut, prawn and vegetables • Contains a portion of Beel Dakatia, the second largest beel (i.e., a lake-like wetland) in Bangladesh	• Characterized by Ganges Tidal Floodplain AEZ • Soil fertility is high and contains medium to high organic contents • Main crops: paddy, wheat, betel leaf, oil seed • Main exports: Hilsha fish, medicine, bidi, handicrafts • Contributes a lot in the production of freshwater fish	• Characterized by Ganges Tidal Floodplain AEZ • Contains a major portion of the Sundarbans • Main crops: paddy, jute, wheat, potato, sesame, linseed, pulse, vegetables • Main exports: shrimp, crab, paddy, jute • Saltwater shrimp culture is extremely popular	• Characterized by Young Meghna Estuarine Floodplain AEZ • Government declared 40 thousand acres of land of the upazila as a national park in 2001 • Main crops: paddy, jute, potato, pulse, oil seed • Main exports: rice, coconut, betel nut, banana, chili, and Hilsha • Nijhum Dwip is a popular tourist spot	• Characterized by the Chittagong coastal zone AEZ • Longest sea beach in the world located here • Most of the upazila is covered with hills and tilas (i.e., small, low hills) • Main crops: paddy, potato, betel leaf, vegetables • Established tourism industries and infrastructure development is tourism-centered

Source: Review of the literature (for example, Mallick, 2019; Agarwal et al., 2019; Adams et al., 2018; FAO and World Bank, 2015) and Government's reports: Yearbook of Agricultural Statistics-2015 (BBS, 2016), Yearbook of Fisheries Statistics of Bangladesh, 2018-19 (DoF) and Bangladesh Disaster-related Statistics: Climate Change and Natural Disaster Perspectives (BBS, 2016), as well as personal communication with Agricultural Extension Officers.

coastal ecosystems (de Jonge et al., 2012). These frameworks might facilitate understanding the interacting ecological and societal processes, predicting change and supporting the management, persistence and resilience of coastal systems as pressures on coastal zones rise. DPSIR is one such framework that has been implemented in coastal zones worldwide to understand and address complicated environmental issues (Lewison et al., 2016). It provides direction for future scenario-based analysis, which allows for formulating and examining probable future coastal zone scenarios (Karageorgis et al., 2006). DPSIR data can be utilized to design integrated coastal zone management (ICZM; Pacheco et al., 2007) and integrated water resources management (Kagalou et al., 2012). Previous researchers have used the DPSIR framework because of its power for communicating results, ability to identify environmental cause-and-effect relationships, interdisciplinary approach, and stakeholder engagement (Bidone and Lacerda, 2004; Giupponi, 2007; Ojeda-Martinez et al., 2009; Atkins et al., 2011; Kelble et al., 2013; Suckall et al., 2014).

In DPSIR, 'drivers' are socioeconomic sectors and the factors that motivate human activities and fulfill basic human needs. 'Pressures' are human activities that induce changes in the SESs. As a result of pressures, the 'state' of the SESs is affected. 'Impacts' refer to the changes in the state of the environment that determine the quality of SESs and the welfare of the human beings who live there. 'Responses' to managing climate change impacts on coastal SESs by individuals, society and policymakers are the result of undesired impacts caused by the drivers, pressures, and state changes (Smeets and Weterings, 1999).

Focus group discussions were conducted to understand and determine local-level drivers, pressures, states, and impacts as well as to prepare a broad list of responses. The day-to-day activities, coping, adapting and mitigating measures adopted by the coastal households were considered as responses.

2.2.2. *Focus group discussions*

Twenty focus group discussions (i.e., four focus groups in each sub-district) were conducted in five sub-districts that represent five coastal SESs. Each focus group discussion contained 8–12 participants. The main purposes for conducting focus group discussions included understanding the drivers, pressures, states, impacts and responses; deriving itemized responses to the drivers, pressures, states, and impacts; and identifying the synergies and trade-offs between adaptation, mitigation and production in coastal SESs. Authors carefully handled the group dynamics between participants to obtain information (Green et al., 2003; Kitzinger, 1994; Thomas et al., 1995). A key criterion for participant selection was heterogeneity of profession and age. Accordingly, the local Sub Assistant Agricultural Officers (SAAOs) and facilitators consulted the lists of village households and selected participants. To secure group attendance, they organized an inception meeting before the focus group discussions. Participants' comfort, access to the venue and levels of distraction were addressed while choosing the venue for focus group discussions. There was adequate seating for everyone to be familiar with each other and with the facilitators. The composition of most groups was heterogeneous, that is, male and female growers, input dealers, NGO professionals, local leaders and businesspeople.

A total of 190 participants took part in these discussions, of whom 75 were female. Female participation in data collection was very necessary as Bangladesh traditionally has a patriarchal, patrilineal, and patri-local social system in which women's voices are suppressed and the society upholds a rigid gender division of labor (MoEFCC, 2013). Moreover, women in coastal regions are increasingly and disproportionately facing food, water, financial and health insecurity (GoB, 2021). Women have less access to such necessities than males, resulting in instability and restricted prospects for equality, social justice and equal survival rights. Furthermore, mixed-gender groups have been shown to increase the quality of conversations and their outcomes (Freitas et al., 1998).

Two research associates and a research coordinator conducted focus group discussions that lasted between 1 and 2 h. The discussions were recorded with the consent of the participants and subsequently transcribed by the research coordinator. Individual and/or community perceptions of the relationships between drivers, pressures, states, impacts, and responses were the focus of our data collection and analysis, since much agrometeorological data were insufficient in Bangladesh (Simelton et al., 2013).

Two questions were developed to guide the focus group discussions based on the study objectives: (a) What are the economic, social and environmental stressors that affect coastal SESs?and (b) How do coastal households' responses (i.e., day-to-day activities) to the multiple stressors affect long-term development, adaptation and mitigation goals? The focus group discussions yielded both qualitative and observational data and responses regarding the drivers, pressures, states, impacts and responses.

The researchers asked participants further questions based on their initial responses to determine their contribution to adaptation, mitigation and production as well as identify synergies and trade-offs between adaptation, mitigation and production in coastal SESs. The contribution of these responses was determined based on the number of times it was mentioned during the focus group discussions,

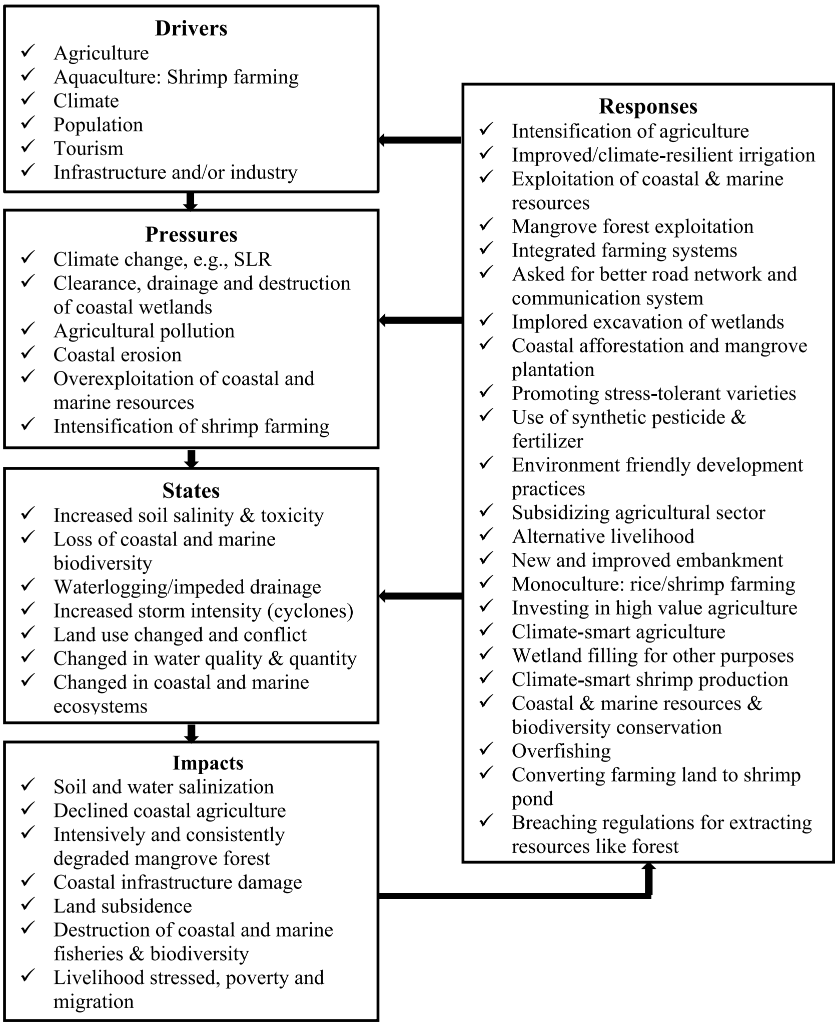

Fig. 2. DPSIR framework for the coastal SESs of Bangladesh.

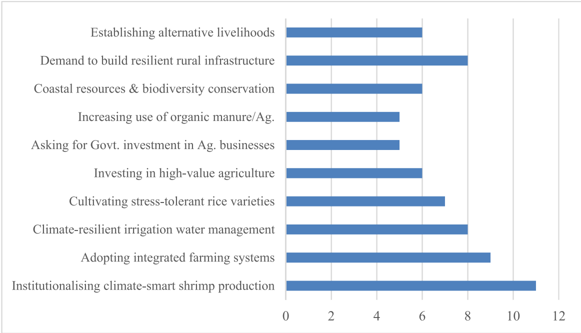

Fig. 3. Ten most-frequently occurring synergies between agricultural production and climate adaptation & mitigation efforts in the coastal SESs of Bangladesh.

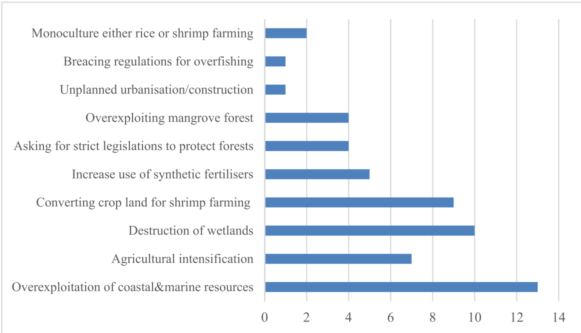

Fig. 4. Ten most-frequently occurring trade-offs between agricultural production and climate adaptation & mitigation efforts in the coastal SESs of Bangladesh.

that is, the more a response was mentioned, and the higher the likelihood that it contributed to adaptation, mitigation and production.

2.2.3. Participatory workshops

A total of five participatory workshops were conducted, one in each coastal SES, to corroborate the responses and findings of the focus group discussions in order to determine major synergies and trade-offs. Workshops were much more collaborative and participatory in nature as well as facilitated in-depth discussions than focus group discussions. These workshops also developed the means and measures to maximize synergies and minimize trade-offs between development, adaptation and mitigation in coastal SESs. A total of 90 respondents attended the workshops, of whom 35 were females. Each workshop had 15 to 20 participants and the sessions lasted about 2–3 h.

Several issues were considered in identifying and selecting the participants, including finding the relevant person, ensuring the right combination of participants and consulting with the participants. Once again, local Sub-Assistant Agricultural Officers played a leading role in recruiting participants for the workshops. A facilitation team was composed of two research associates, a research coordinator and a Sub-Assistant Agricultural Officer who had agreed to contribute to the subject matters. Introducing participants, facilitating participants to get to know each other, developing ground rules, and summarizing the workshops were key steps of workshop planning. The length of the workshop and themes of discussion were determined beforehand. Essential instruments like drawings, charts and flashcards were arranged.

The main workshop had four phases. In the first phase, a brief overview (objective, goal and methods) of the workshop was presented by a facilitator. In the second phase, the specific responses to the drivers, pressures, states, impacts and responses derived from the focus group discussions were discussed and reviewed. In the third phase, major synergies and trade-offs were determined. In the fourth phase, measures aimed at maximizing synergies and minimizing trade-offs were identified. In these determinations, the greater the frequency of synergies, trade-offs, and associated measures; higher was the possibility of influencing the results and conclusions. A variety of instructional tools (such as drawings, charts, flashcards, videos and objects) were utilized to supplement creating and obtaining responses to drivers, pressures, states and impacts.

3. Results and discussions

The DPSIR framework for the five coastal SESs is presented in Fig. 2. It depicts the key drivers (e.g., agriculture), pressures (e.g., sea level rise), states (e.g., increased salinity), impacts (e.g., salinization) and responses (e.g., intensification of agriculture). The overall

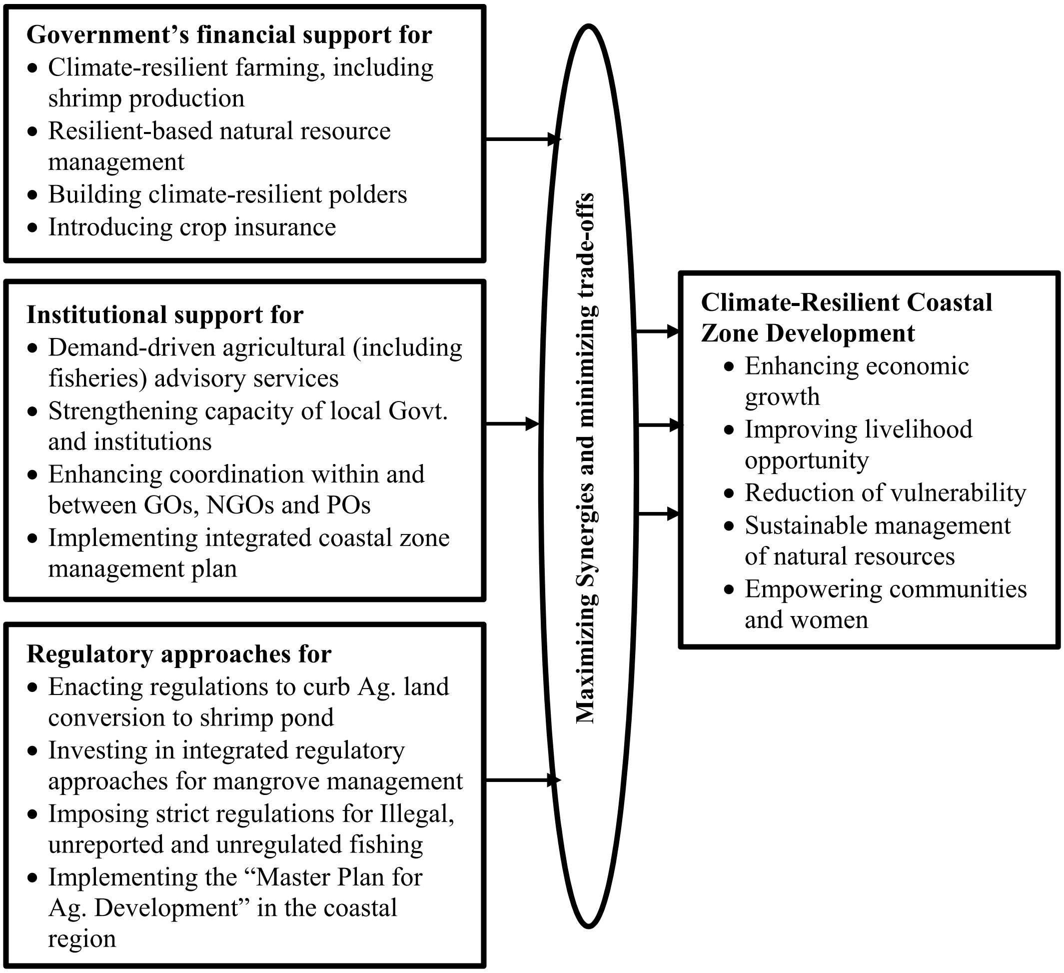

Fig. 5. Means or measures to maximize synergies and minimize trade-offs between development (productivity), adaptation and mitigation towards building climate-resilient coastal zones.

results showed that synergies were more prevalent than trade-offs in the coastal SESs examined (Figs. 3 and 4, and Supplementary 1–5). Maximizing synergies and minimizing trade-offs were closely linked to the speed and scale of adopting climate-resilient and/or -smart approaches to achieve multiple societal objectives (Supplementary 1–5). Adoption of these approaches can be enhanced by creating favorable conditions for financial, institutional and regulatory support and will subsequently lead to climate-resilient coastal zone development that will foster economic growth, improve livelihood opportunities, reduce vulnerability, allow proper management of resources, and empower communities (Fig. 5).

3.1. *Major synergies*

Both saltwater shrimp and freshwater prawn production (Supplementary 3) have been increasing from the south-eastern to the south-western coastal regions in Bangladesh because of favorable climatic conditions and abundant resources such as feed, seed, water and a cheap labor force (Islam, 2003). The fast expansion of shrimp production has resulted in immediate and long-term environmental consequences including ecological imbalance, pollution and disease outbreaks (Hossain et al., 2013). The destruction of the mangrove ecosystem, land degradation, saltwater intrusion, loss of captured fishery stock, severe scarcity of seed supply, sedimentation issues and gene pool alteration are other major problems related to saltwater shrimp production (Paul and Vogl, 2011).

To combat these issues, *climate-smart shrimp production systems* (Figs. 2 and 3) should be developed based on the most appropriate techniques considering both traditional (e.g., no artificial feeds or antibiotics) and innovative (e.g., organic farming) practices. Climate-smart shrimp production leverages synergies through achieving sustainable aquaculture production systems, reducing climate vulnerability and contributing to the mitigation of GHGs (FAO and World Bank, 2015). Farmers gain directly from climate-smart integrated aquaculture through adaptation of locally suitable practices (e.g., farming of stress-resistant fish species to cope with changing environmental conditions) and context-specific technologies (e.g., promoting integrated crop-fishery systems; Trinh et al., 2016). Women participants usually involved in small-scale fish culture. To make their small-scale fisheries sustainable they demanded active engagement of local institutions with their necessary support services e.g., fund, technologies, training. Climate-smart shrimp production must be institutionalized through positive changes in the institutional framework, sound policies (e.g., ensuring water tenure and strengthening social protection safety nets), robust local institutions and financing mainstreaming climate-smart aquaculture (FAO and World Bank, 2015; Troell, 2009).

Traditional farming techniques dominate the coastal SESs. The findings of this study reveal that *integrated farming systems*, including prawn-carp-rice, shrimp-rice-vegetable cultivation and fish/fruit/forest farming, were suitable solutions for food security, adaptation, mitigation and long-term livelihood. These farming systems were conceived by combining appropriate farming components that need less land and time while maintaining a consistent income for the farmers. An integrated farming system is more sustainable compared to monoculture (e.g., shrimp production) for compatibility, durability, efficiency, equity, productivity and stability related to coastal agriculture (Talukder et al., 2015). Integrated farming systems maximize synergies by properly using farm resources, increasing farm production, preventing environmental degradation, improving the quality of life for poor farmers, and preserving sustainability (Al Mamun et al., 2012). Integrated farming stresses the interdependence of various agricultural products as well as the conservation of natural resources such as water, soil and air quality (Talukder et al., 2016; see Figs. 2 and 3).

For instance, *Macrobrachium rosenbergii* (i.e., giant river prawn) farming has recently launched in the coastal areas of Bangladesh. The government of Bangladesh has aided poor and marginalized women farmers in adopting integrated farming systems with the help of the Danish International Development Agency (DANIDA). As a result, *M. rosenbergii* has been raised alongside filter feeder carp (*Hypophthalmichthys molitrix/Catla catla*), rice, and vegetables on dikes (Azad et al., 2005). Dike cropping (Supplementary 1, 2, 3 and 5) was also used by farmers in the coastal zones. Banana plants were grown on gher dikes by farmers, and banana leaves have been used for feeding grass carp (*Ctenopharyngodon idella*). Small-scale integrated gher farming has become a low-risk venture with a healthy profit margin (Azad et al., 2005; Islam et al., 2004). The locally used term "gher" refers to building higher dikes around the field and digging a deep canal inside the periphery to preserve water during the dry season (Kendrick, 1994).

Just like other South Asian countries, Bangladesh has major water management issues including weak institutions and insufficient standards for transboundary water management (Chan et al., 2016; Price, 2016). While climate change plays a minor role in the emergence and worsening of water conflicts (Kloos et al., 2013) it is expected to have a variety of adverse effects for a low-lying delta region like Bangladesh. Food shortages could become more common as a result of climate-related changes such as glacier melting and high precipitation events. More evaporation and transpiration are expected because of rising temperatures, which reduce the productivity of agriculture and increase reliance on irrigation (Lobell et al., 2007). All of these factors may have significant implications for the region's agriculture, fisheries, livestock, food and livelihood security. Climate-driven water shortage has been projected to limit GDP growth rates in the region by as much as 6% if current trends continue (www.worldbank.org). Thus, *climate-resilient water management technologies* such as buried pipe irrigation systems, rainwater harvesting, solar-powered irrigation systems, and system of rice intensification (SRI) have been very significant to enhance synergies between productivity, adaptation and mitigation (Fig. 3).

Climate change and accompanying adverse climatic conditions have wreaked havoc on Bangladesh's enormous coastal infrastructure. Building *climate-resilient rural infrastructure* will help develop climate-resilient communities that can cope with climatic shocks and stresses quickly (Fig. 2). This infrastructure can be in the form of building improved roads, houses, dams, bridges, embankments, educational institutions. Rural areas in Bangladesh will experience substantial economic growth over the next decade, driven by an array of rural infrastructure development initiatives supported by the organizations such as the Asian Development Bank and the World Bank (Srinivasan and Gibb, 2019). For instance, the Coastal Climate-Resilient Infrastructure Project (CCRIP) is a US $150 million rural infrastructure project that has been undertaken in 12 districts in Bangladesh. The project is intended to increase farm and family connections in the face of climate shocks, with an emphasis on strengthening the resilience of key community infrastructures (e.g., roads) and irrigation canals (Arslan et al., 2019).

The findings of the study indicate that *cultivating stress-tolerant rice varieties* is an important synergy (Fig. 3) since these technologies ensure increased production and resilience. Women participants were particularly eager to produce stress-tolerant crops, fisheries and livestock varieties. Previous studies have indicated that climate change has negative impacts on agriculture at both global and national level (e.g., Basak et al., 2009; Lobell et al., 2007). In particular, floods, soil salinity and droughts are the major extreme climatic events that have adversely affected agricultural production in Bangladesh (Dasgupta et al., 2014). As the coastal zones are low-lying lands and a substantial number of areas are exposed to salinity, crops are prone to climatic hazards (Government of Bangladesh, 2021). The Bangladesh Rice Research Institute ([BRRI], 2014) has developed 24 stress-tolerant rice varieties that support adaptation by minimizing stresses and mitigation by requiring less irrigation and producing less GHGs such as methane and nitrous oxide. Rice varieties such as *BRRI dhan 47* and *BRRI dhan 67* can withstand salinity of up to 12–14 ds/m during the vegetative growth stage, providing significant protection from the adverse effects of sea level rise (BRRI, 2014). However, dissemination of these varieties to the coastal growers has been unsatisfactory (Roy et al., 2013; Roy et al., 2019) and requires immediate action. In the medium term, producing stress-tolerant rice varieties can be the best intervention for coastal agricultural systems (Ahmed et al., 2016).

Workshops revealed that *high-value agriculture* can be complemented by investing in industrial crops (e.g., cotton, tobacco and jatropha production; Figs. 2 and 3). Women participants identified high-value agriculture as an important synergy for coastal SESs because it supplies resources for high-value-added goods and bioenergy, increasing farmers' incomes and boosting coastal economies. These results are consistent with the findings of other researchers such as Wiggins et al. (2015) and Singh (2010). The relative significance of grains and other starchy staple crops is dropping in the developing world, while the importance of high-value agricultural commodities is growing. The nature of agricultural supply channels, prospects for small farmers, and the role of public policy and investment have all been profoundly affected by the revolution of the agricultural industry. The expansion of high-value agriculture (Figs. 2 and 3), in particular, has necessitated closer ties between farmers, processors, dealers, and retailers to manage supply and demand (Gulati et al., 2006). Income growth is a crucial driver of increased demand for high-value agricultural goods because they have strong income elasticity as relatively expensive sources of calories.

Recently, Asia has seen a fast economic expansion that has increased the local demand for high-value agricultural goods. Over the period of 1990–2002, China and Vietnam witnessed the most rapid rates of per capita GDP growth, at 8.6% and 5.7%, respectively, while Bangladesh, India, and Thailand all saw annual growth rates of greater than 3% (World Bank, 2005). Fruits and vegetables, fish, meat and dairy products, all of which are high-value commodities, have become increasingly important in the food consumption basket. In rural and urban regions, these goods were previously estimated to account for 40% and 49% of the food consumption baskets, respectively (USAID and EU, 2022). Bangladesh will annually consume an additional US$12 billion of these high-value items by 2025, according to demand projections based on sustainable growth rates in income and population (GED, 2020).

Establishing alternative livelihoods was noted as a significant synergy (Figs. 2 and 3). It is obvious that in the aftermath of a catastrophe, a community's ability to manage post-disaster vulnerabilities will be hampered by a lack of livelihood opportunities combined with poor and unstable household conditions. In these circumstances, alternative livelihoods could open up a wide range of possibilities for the coastal people. These alternative livelihood options include promoting tourism, building self-help community groups, local entrepreneurship development, context-specific livelihood options and promoting indigenous knowledge and skills-based livelihood strategies. Investing in coastal and marine eco-tourism in Cox's Bazar Sadar (saltwater shrimp production SES), Hatiya, Noakhali (rainfed agriculture SES) and Shyamnagar, Satkhira (mangrove-dependent SES) are options for generating alternative livelihoods (Supplementary 4 and 5).

3.2. Major trade-offs

The coastal SESs are full of coastal and marine resources that have been harvested since time immemorial (Agarwal et al., 2019) (see Supplementary 1–5). Most of the Bay of Bengal's commercially important aquatic (fish) species, such as *Hilsa ilisha*, *Pangasius pangasius*, *Plotossus canius*, and *Scylla serrata*, have been overexploited (Canonizado and Hossain, 1998). Pollution of coastal and marine ecosystems has been a growing concern for the long-term sustainability of fisheries (Islam, 2003). Wild animals in the coastal zone are becoming endangered due to habitat destruction and unauthorized hunting (Islam, 2003).

Due to a lack of proper implementation of various strategies (e.g., Coastal Development Strategy, 2006), policies (e.g., Coastal Zone Policy, 2005), and other instruments, people have been deteriorating these diversified ecosystems (Figs. 2 and 4). One example is the disappearance of the mangrove forests along the coastline of the Cox's Bazar district. The focus group members indicated that the overuse of forest resources for fuel wood, high grazing pressures, fishing, human habitation, salt manufacturing and shrimp production have been major drivers that have resulted in the complete disappearance of mangrove forests and their rich biological diversity in that district. Furthermore, fishers have constructed dams at the mouths of streams which prevent tidal inundation and cause water stagnation. Seedlings in stagnant water cannot survive as a result of the shift in hydrology, which is posing a major threat to forest regeneration (Siddiqi et al., 1994). These interventions, along with the government's strategy of opening up mangrove forest reserves to shrimp farms and human habitation, has resulted in the mangrove being severely depleted in the coastal zones. Similarly, polders (i.e., circular dyke networks to protect low-lying lands from flooding), a major regional intervention, limit tidal inundation and nutrient exchange, affecting ecosystem and ecological services. (Figs. 2 and 4).

The forest resources in the coastal areas of Bangladesh have not been well protected (Supplementary 5). The widespread development of saltwater shrimp production in the coastal areas of Bangladesh has resulted in ecosystem simplification by turning the multifunctional mangrove ecosystem into private shrimp ponds. Mangrove loss has been linked to a number of significant concerns, including biodiversity loss, habitat degradation, and a huge amount of carbon dioxide released into the atmosphere. The mangrove loss in Bangladesh coastal SESs is similar to a pattern seen throughout the Asia and the destruction of mangroves represents the destruction of a large carbon sink (Uddin et al., 2014; Páez-Osuna, 2001).

Wetlands are vital to Bangladesh's economic, industrial, ecological, socioeconomic and cultural development (FAO, 2012; Islam and Gnauck, 2008). Moreover, wetlands are considered one of the most biodiverse areas which consist of many important habitats (http://www.warpo.gov.bd/). Coastal as well as mangrove wetlands are a unique floral-faunal assemblage habitat, offering a complex detritus-based food web for a variety of marine and saltwater species (Islam and Gnauck, 2008). Therefore, *destruction of coastal wetlands* and overexploitation of their ecosystem services have had a negative impact on mitigation potential and served as a significant trade-off (Figs. 4 and 2).

Since its beginning in the 1970s, saltwater shrimp production has wreaked havoc on coastal ecosystems in Bangladesh (Fig. 4). Respondents noted that unregulated and traditional shrimp production is a major trade-off for adaptation goals (e.g., addressing soil salinization). *Continuous and unregulated shrimp production* has had enormous impacts on human well-being, ecology, the environment and sustainability even as it has increased income, brought in profits and strengthened the local economy. The commercialization of shrimp production has accelerated all the negative impacts of shrimp production as the farming became much more intensive (Fig. 2 and Supplementary 3). Consistent with the results of Islam and Bhuiyan (2016), the current findings show the socioeconomic effects of shrimp production including traditional livelihood dislocation, alterations in agricultural patterns, food insecurity, reduced social security, displacement and marginalization, local unrest and social conflicts.

Coastal and marine fishers in Bangladesh catch roughly five million tons of fish every year, accounting for a total of 15% of the country's total fish production (Department of Fisheries, 2019). The potential of coastal fisheries has not been properly used since fish stock has been overexploited (Supplementary 4), partly due to lack of regulations to protect the fisheries of the coastal SESs. Managing marine fisheries is difficult due to a lack of proper monitoring and ineffective implementation of various rules and regulations. For instance, the Protection and Conservation of Fish Rules (1985) has guidelines for fishing methods including fish species that cannot be caught during a specific season, mesh size of fishing nets and the prohibition of landing and carrying fish of a specific size. However, the reality is different as challenges such as the lack of institutional coordination, efficient workforce, and accountability hindered the initiatives (see Khan, 2010).

Intensive tillage has been used for planting, weeding, and loosening the surface and subsurface soil, which helps to relieve GHG emissions from crop fields. Nevertheless, *intensive crop farming* degraded soil and environmental quality as well as emitted huge amounts of GHGs (Hamza and Anderson, 2005, Figs. 2 and 4). Rice monocultures that were maintained intensively resulted in increased soil compaction, poor soil quality, and GHG emissions (Ba et al., 2015). Soil fertility in the coastal zones has been declining due to intensive (paddy) farming (GED, 2018). Paddy fields are the most common agricultural land use that significantly impacted the carbon cycle and contributed to global climate change (Ren et al., 2007). According to the FAO database, rice agriculture accounted for 10.1 percent of total agricultural GHG emissions globally (FAO, 2012). Paddy habitats are thought to be a carbon sink for CO_2 in the atmosphere and they are sensitive to changes in the C pool (Kuzyakov and Chen, 2004). Various tillage and nitrogen fertilizer management strategies greatly impact the carbon cycle in these systems (Ding et al., 2006). Intensive agricultural activities by cutting down (mangrove) forests have also contributed to the negative impacts on coastal SESs.

3.3. Measures to maximize synergies and minimize trade-offs

3.3.1. Government financial support

The creation of policy instruments (e.g., Mujib Climate Prosperity Plan - Decade, 2030) shows that the government has increased and will increase financial support for improving and changing the landscapes of coastal agriculture, including the forest, fishery and livestock sectors. However, these supports have been insufficient to cope with the current impacts of coastal flooding and water-logging, let alone lead to long-term development. Specific financial resources are required to generate and disseminate an authoritative account of beneficial farming practices, technologies and services.

Simultaneously, raising growers' awareness and improving their knowledge, skills and access to technologies have to be ensured. These can lead to resilient crop, fishery and livestock production systems. Initiatives are required to incorporate resilience principles (namely, maintain diversity, broaden participation, encourage learning and manage connectivity) in managing natural resources (Biggs et al., 2015). The Department of Agriculture, Department of Fisheries, and Department of Livestock Services (DLS) have significant roles in addressing these interventions (Fig. 5). Discussions with workshop participants revealed that developing climate-resilient agricultural extension services was long overdue in the coastal zone. Salient features of these services are pluralistic, bottom-up, institutionalized climate field schools and strong public-private partnerships.

Polders major interventions that help to increase food production in the coastal zone, but they are subject to second-generation social and environmental problems such as siltation, salinity, waterlogging and drainage (FAO, 2012). Polders require restructuring with appropriate design so that they can withstand rising sea levels and storm surges. This restructuring must have regular and effective operations and maintenance. Farmers require micro insurance and long-term agriculture and livestock insurance. Our field observations indicated that sustainable development in the agricultural sector is not possible without introducing insurance coverage. The government provides various forms of financial assistance (i.e., subsidies) which can be used to fund and promote crop insurance, considering the challenges of supply and demand. It is crucial to address pertinent concerns including formulating a policy guideline, reducing value-added taxes and developing actuarial capabilities of the insurance regulators.

3.3.2. Institutional support

In light of the changing climate, the DAE, DoF and DLS must be revamped in order to address institutional challenges. Likewise, local governments need an overhaul to contribute to local planning and policy implementation by offering their facilitative capacity, local leadership, bargaining power, local cooperation and coordination mechanisms. The focus group and workshop participants indicated that maximizing synergies and minimizing trade-offs between production, adaptation and mitigation in the coastal SESs require policy coordination between government ministries and institutional coordination among the GOs, NGOs and POs to design, deliver, evaluate and implement coastal policies and strategies. However, these coordination mechanisms have been largely contingent on a comprehensive diagnosis of the challenges faced by institutions (i.e., rules of the game) and organizations (i.e., players of the game).

Implementing Integrated Coastal Zone Management (ICZM) plans is another key issue for maximizing synergies and minimizing trade-offs in the coastal zones. Implementing these plans involves three broad issues: (a) mainstreaming climate adaptation concerns into, inter alia, agriculture, water, land and irrigation policies to increase the effectiveness of measures deployed for reducing the causes and impacts of climate change; (b) a considerable investment in nine strategic priorities (e.g., optimizing use of coastal lands and environmental conservation) as identified by the Coastal Development Strategies (http://www.warpo.gov.bd/); and (c) strengthening governance scaffolds that primarily focus on developing institutional capacity and legal frameworks so that over-exploitation of coastal and marine resources can be curtailed.

3.3.3. Regulatory approaches

Coastal lands, wetlands and mangrove forests have been facing a multitude of problems. Climate-resilient coastal zone development is hard without conserving and improving coastal resources. An increasingly important concern is to address coastal land use conflicts between crop and shrimp production. The MoA and Bangladesh Water Development Board (BWDB) must devise mechanisms to deal with these conflicts. Bangladesh still does not have regulations to curb the conversion of cropping land to shrimp production. Similarly, there are few useful legal and administrative monitoring and surveillance mechanisms to combat illegal, unreported and unregulated (IUU) fishing activities in Bangladesh's maritime zones. Policy instruments such as the Protection and Conservation of

Fish Act of 1950 and the Marine Fisheries Ordinance of 1983 lack comprehensive mechanisms to thwart unauthorized fishing activity. To seize the potential of the blue economy, investing in strengthening ocean governance, that is, formulating and effectively implementing aquaculture management policies and taking precautionary principles into account, is warranted.

The Sundarban mangrove forest not only saves coastal regions from natural hazards but also protects coastal agriculture, biodiversity, marine resources, and the livelihood of the coastal communities (Agarwal et al., 2019). The degraded mangrove ecosystem in Sundarban is one of the most significant trade-offs of coastal development. Agricultural activities and shrimp production must be stopped in the Sundarban. Mangrove management should be a part of the Coastal Zone Policy (MoWR, 2005) and Coastal Development Strategy (MoWR, 2006) and, above all, the ICZM Plan. Proper implementation of the Master Plan for Agricultural Development in the Southern Region of Bangladesh could bring many benefits, including conserving and protecting mangrove forests. Planning exercises should emphasize a local stakeholder-centered focus so that implementing this plan yields maximum benefits for the coastal communities. Furthermore, a strong institutional framework that pays particular attention to coordination between the different organizations, ministries and departments is required.

4. Conclusion and recommendations

The economic development of Bangladesh is considerably reliant on the coastal SESs. This study determined synergies and trade-offs and developed measures (namely, government's financial, institutional and regulatory support) for maximizing synergies and minimizing trade-offs between adaptation, mitigation, and development in five coastal SESs in Bangladesh. Major synergies including climate-smart crops and shrimp farming and the development of resilient rural infrastructure to achieve development goals while reaping the multiple benefits of climate change management. The major key trade-offs are overexploitation of coastal and marine resources and transforming land use from wetlands or cropland into shrimp production. These trade-offs have had adverse impacts on sustainable coastal development.

Based on the findings, we designed three broad measures for maximizing synergies and minimizing trade-offs for building climate-resilient coastal zones in Bangladesh (Fig. 5). These measures will result in a range of outcomes including fostering economic growth, increasing livelihood opportunities, reducing vulnerability, promoting sustainable resource management, and empowering communities. Based on the findings, we draw policy implications in four domains:

- Develop innovative financial mechanisms to encourage the adoption of climate-smart and/or -resilient agricultural technologies. Prioritize key areas for financing including improving surface water irrigation systems, upscaling community-based dairy farming, promoting community-based pen and cage culture and encouraging mixed fruit orchard production. Large financial investments are required for the sustainable intensification of coastal agricultural systems.
- Strengthen coastal and marine resource stewardship by creating an increasingly strict regulatory environment and employing resilience principles. Enforce existing laws and regulations to protect the bulk of natural resources, even though they are currently insufficient to fully safeguard the mangrove forest, coastal wetlands and IUU fishing. Institutionalized resilience principles such as maintaining diversity, encouraging learning, broadening participation and promoting polycentric governance will help the residents learn how to conserve coastal and marine resources.
- Invest in the sustainable intensification of polder agriculture to enhance the livelihood resilience of polder communities. The government should renovate and rehabilitate polders and consider climate-resilient coastal protection and management. Polder agriculture can be improved and diversified through scaling up community-driven approaches (e.g., community-based open water stocking) for sustainable intensification.
- Strengthen coastal institutional scaffolds. A sustainable institutional framework is yet to be put in place at different levels. A people-centered focus must be embedded in polder management. Multi-level and multi-sectoral collaboration involving ministries (MoA and MoWR), departments (DAE and DoF) and other entities (WARPO) will be indispensable for implementing ICZM and the Master Plan for Coastal Agricultural Development.

Declaration of competing interest

The authors declare there is no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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