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Agriculture and fisheries production in a regional blending and dynamic fresh and saline water systems in the coastal area of Bangladesh

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ABSTRACT

With the increase of salinity, shrimp monoculture is a typical production system on many global coasts. They are thus inviting commercially valuable exotic shrimp species that threaten the population of natives and causing alteration of ecosystem function. This intentional introduction and redistribution of shrimp species is an Anthropocene feature of the global coast. Therefore, we investigated how the coastal system breaches a freshwater system leading to more saline-friendly production. Spatiotemporal mapping showed the scope of diversified coastal livelihood that illustrate the coexistence of saline and sweet water-based production system in Bangladesh with a mean accuracy of 89% (kappa statistics 0.86). In many parts, the once agriculturally dominated landscape has transformed into aquaculture to produce shrimp, crab, fish, and salt. Continuous Change Detection and Classification (CCDC) algorithm also depicts the breakpoint in time series of normalized difference vegetation index (NDVI) data due to coastal land-use change. This dynamism includes the strong presence of mixed rice-shrimp culture in Assasuni (west coast) and Chakaria (east coast), as well as salt panning in Chakaria and paddy rice production in Kalapara (mid-coast). Thus those areas are more resilient because many other coastal communities primarily depend on shrimp or aqua monoculture, having limited or no alternative production system. Due to semi-intensive shrimp cultivation, biotic depletion, disease, pollution like antibiotics, nutrients, and organic matter loads are also less than the global coast's intensive aquaculture area. This study revealed the need for a blended fresh and saline-based production system. The findings can be used as a reference in the formulation and implementation of sustainable coastal management policies.

1. Introduction

The interaction between land and the sea is a dominant factor in coastal areas, which experience unique hazards, and coastal inhabitants worldwide are becoming exposed to increasing levels of natural calamities (Shaw & Krishnamurthy, 2012; Thomas & López, 2015; Abdullah et al., 2013; Abdullah et al., 2019). These calamities include cyclones, sea-level rises, waterlogging, increased salinity, and land subsidence (Lenzen et al., 2019; Hasnat et al., 2019; Islam et al., 2018; Rakib et al., 2019; Wang et al., 2018). Further, climate change has impacted human well-being, security, and livelihood in coastal areas by limiting the chances of disaster recovery (Brown et al., 2007; Lebel, 2012; Hossain et al., 2016; Hossain et al., 2017; Abdullah & Rahman, 2015; Toufique and Yunus, 2013).

Predicted global mean sea level showed a rise of 0.30-0.65 meters by 2100 and 0.54-2.15 meter by 2300 relative to 1986 to 2005 (Horton et al., 2020; Smajgl et al., 2015). Salinity intrusion and sea-level rise traditionally impacting the coastal areas, so further increases in sea level would only increase the burden of coastal communities in terms of daily life and livelihood (Miah et al., 2017; Glade & Alexander, 2013; Nicholls et al., 2007; Cameron et al., 2021). Due to coastal inundation shrimp aquaculture area is expanding (Morshed et al., 2020; Jayanthi et al., 2018; Primavera, 1997). Coastal communities in Asia produced more than 70% of cultured shrimp, while facilities in the continental United States produced the remainder (Silverman et al., 2019; Valderrama et al., 2017).

In Asia, China, Vietnam, Thailand, Myanmar, India, and Bangladesh are the major shrimp producers (Yang et al., 2017; Boyed et al., 2017; Lebel et al., 2016; Veettil et al., 2018; Mohanty, 2018; Abdullah et al., 2017). Huge economic return, shrimp farming showed a thriving growth and became a 45-billion-dollar industry, producing 4.66 million MT of shrimp in 2018 with a forecasted compound annual growth rate of 5.2% increase during 2019-24 (FAO, 2019). Though sea level increases lead to more production diversity over the traditional single-crop rice

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production in coastal areas, the new production systems have many adverse consequences (Islam & Tabeta, 2019; Tobey et al., 2017; Walton et al., 2002; Páez-Osuna, 2001; Huda et al., 2019). Large scale shrimp aquaculture causes traditional livelihood displacement (Hossain et al., 2013; Hamilton, 2011), food insecurity (Islam & Bhuiyan, 2016; Primavera, 1997), marginalization (Rijanta, 2017; Halim, 2004), rural unemployment (Afroz & Alam, 2013; Swapan & Gavin, 2011;), social unrest (Islam & Bhuiyan, 2016; Stonich & Vandergeest, 2001; Flaherty & Karnjanakesorn,1995), and, land grabbing (Blythe et al., 2015; Pokrant, 2014; Datta et al., 2010; Abdullah et al., 2019). Environmental concerns include invasive species introduction (Alatorre et al., 2016; Zabbey et al., 2010), mangrove degradation (Malakar, 2020; Alatorre et al., 2016; Erftemeijer, 2002; Huitric et al., 2002), loss of biodiversity (Elwin et al., 2020; Haider & Akter, 2018), sedimentation (Anh et al., 2010), saltwater intrusion (Islam & Tabeta, 2019; Paul & Vogl, 2011), organic matter loading (Barraza-Guardado et al., 2013; Páez-Osuna et al., 1999), pollution (Santacruz-Reyes & Chien, 2012), antibiotic contamination (Thornber et al., 2020; Thuy & Loan, 2011) and emission of greenhouse gas (Jonell & Henriksson, 2015).

So, the tradeoff between economic value and socioecological consequences of shrimp farming is needed to be reconciled for a sustainable coastal future. For instance, coastal farmers in Bangladesh utilize shrimp and crab farming and salt production in addition to conventional crop production to maximize the potentials of blended sweet and saline water-based production at the spatial and temporal scale. Much of the past research has been carried out regarding various opportunities and challenges of shrimp monoculture in the global coastal areas. However, most of the global study overlooked the need for a comprehensive production system including blended sweet and saline water for future coastal sustainability. The paper explored how saline water breaches the freshwater systems and why both agriculture and fisheries are required to continue as a coastal practice. We explained these situations from the coastal co-production example from Bangladesh.

2. Material and methods

2.1. Study area

The coastal area is the place where land and sea meet to create a distinct ecology and environment. The area possesses unique characteristics of mixing sweet water with saline water, often called brackish water. According to the world resource institute, the total length of the global coastline is 1,634,701 km (Wikipedia, 2020), in which an area of ~23,330 km^{-2} is used for brackish water shrimp production (Verdegem & Bosma, 2009). In Bangladesh, out of 700 km long coastline, 2160 km^{-2} is under brackish water shrimp cultivation. Three distinct coastal regions are observed in the country, which is divided into the west, middle/central, and east part. The study areas were selected randomly based on their role in the saline-fresh water production system.

The Assasuni sub-district (occasional paddy field), which is situated within the Satkhira district, was selected to represent the west coast; the Kalapara sub-district (paddy rice dominated), situated in the Patuakhali district, was selected to represent the middle area of the coast; and the Chakaria sub-district (salt-aquaculture-paddy rice mixed), situated in Cox's Bazar District, was selected to represent the east coast.

Historically, Chakaria was a mangrove forest until 1990 (Islam et al., 2019); after that, gradual forest loss occurred, and the area was converted to shrimp and salt production, and Assasuni was a rice production area, which was transformed into aquaculture during the 1990s (Prince et al., 2018). Natural calamities, extreme events, salinity intrusion, inundation, lower agricultural productivity, poverty are socioecological challenges common to each study site (Hasan and Kumar, 2020; Islam et al., 2018).

2.2. Data acquisition and processing

Two different satellite images, the Landsat (TM-Thematic Mapper and MSS-Multispectral Scanner) and the Sentinel-2 Multispectral, were used in the study based on their availability to provide cloud-free historical and present data. Sentinel-2 was launched in 2015, so to obtain previous data, we used Landsat historical imageries. Landsat satellite has a coarse resolution of 30 m, whereas Sentinel-2 provides a finer resolution of 10 m, which helps in more accurate object identification and image classification. This 10 m finer resolution has proven its utility for coastal and inland waters monitoring. Besides, those satellite imageries are freely available for spatial analysis.

For Assasuni, Kalapara, and Chakaria, listed imagery was used (Supplementary table: 1). All the images were downloaded from the United States Geological Survey website. The European Petroleum Survey Group (EPSG) code for each image is 3106. Temporal data for 2016–17 were collected for November 2016 and February 2017 as clear, cloud-free images were available at that time. In Bangladesh, November is considered post-monsoon, while February is pre-monsoon. The key features of the satellite images are provided in the supplementary table.

After downloading the Landsat satellite surface reflectance imagery (atmospherically corrected), multiband composite imagery was created using bands 4, 5, 6, and 7 in the Landsat-1TM satellite and bands 5 to 4 and 3 in the Landsat-8 satellite in QGIS 2.3. Atmospheric correction of Sentinel-2 imagery was done using Sen2cor in the Python environment. Sen2cor is a standalone atmospheric and terrain correction software for Sentinel-2 imagery. It also corrects the effects of aerosol, haze, and vapor for clouds and includes a quality indicator (Louis et al., 2016). All the bands were then converted to surface reflectance (SR). Multispectral satellite imagery pre-processing for classification is done to create an enhanced satellite image before further processing and analysis. A shapefile of each study area was extracted from the sub-district level shapefile of the Bangladesh country shapefile. The study area imagery was clipped. Upon completion of the atmospheric correction, a multiband image was created using bands 2, 3, 4, and 8. A multiband false-color composite image is useful to identify earth surface features under investigation. Image processing was done to remove the inherited artifact for further processing.

The image classification's primary purpose is to categorize and quantify the different earth objects as represented by land use and land cover of the particular area. Image classification was carried out with two different approaches, one for each satellite imagery type. For the Landsat imagery, pixel-based classification was carried out, as the resolution of the Landsat imagery is 30 meters, which is coarser in terms of spatial resolution than Sentinel-2 (10 m). For those Landsat images, QGIS 2.3 software was used to generate training data according to the study area's different classes. Training data were generated as a polygon shapefile. Based on the training, data classification was carried out in RStudio. For the Chakaria sub-district, 40 training data were generated for four different classes, and, later, using the R script, the image was classified in RStudio. Due to their excellent resolution, object-based image classification was carried out in Sentinel-2 imagery. Segmentation of the clipped Sentinel-2 imagery was performed using eCognition software with a scale parameter of 50, shape 0.1, and compactness 0.5 in the homogeneity criterion composition. The main goal of image segmentation was to identify the shrimp farm from other land use. It also gives us a piece of quantitative information on spatiotemporal land use and land cover at each study site. The final classified map was completed in ArcMap 10.5. A field survey was conducted to validate the shrimp pond and rice paddy field mapping effort during January 2017 and 2018. The survey includes a Global Positioning System (GPS) data acquisition and recording farms' precise coordinates.

The CCDC algorithm was applied to the landsat historical data record/ archive in google earth engine to know the changes in existing LULC in a particular site (Zhu & Woodcock 2014). This algorithm is capable of detecting many kinds of land cover change as new images

Table 1
Spatial and temporal coverage of significant land use in the study area

Sub-district	Total area(Ha)	November 2016			February 2017			OverallAccuracy (%)	Kappa
		Aquaculture(Ha)	Cropland(Ha)	Salt(Ha)	Aquaculture(Ha)	Cropland(Ha)	Salt(Ha)		
Assasuni	37,846	18,244	4,533	-	17,895	2,657	-	91	0.87
Kalapara	48,310	-	28,512	-	-	-	-	95	0.91
Chakaria	97,032	12,235	2,526	-	6,977	3,116	5,856	82	0.79

are collected and at the same time provide land cover maps for any given time. For better identification of land cover change, a two step cloud, cloud shadow, and snow masking algorithm is used for eliminating "noisy" observations.

This paper is a combination of a remote sensing analysis and systematic review. During the review, journal publications, various relevant books, reports from international organizations, and daily newspapers were gone. Initially, *Google Scholar* was used to exploring what types of articles are available. However, as the search result was heavily confined within peer-reviewed journals, we have to opt for the *Google Search* engine. Among the online database, *Scopus* (Elsevier) and *Web of Science* (Clarivate Analytics) were gone through. Most relevant results were found while searching using the following keywords: *"Shrimp farming", "Shrimp monoculture", "Coastal Production system", "Saline water dynamics"*. Those terms were selected for their appropriateness and relevance to the study. The period was chosen from 2000–2020. Though the searching period was extensive, most of the information regarding shrimp farming was from the year 1980. After collecting all the available information, it has been presented as per the objectives of this paper.

3. Results

The rising of sea levels is scientifically proved, and it also affects the extent of saline and brackish water bodies in global coastal areas. Coastal areas are highly threatened by sea-level rise, and consequently, saltwater intrusion is increasing day by day. Over the years, coastal shrimp farming is considered an adaptation mechanism that results in further intrusion of saline water on the global coast (Islam et al., 2018). Salinity intrusion and increased salinity in water and soil have severe negative impacts on agriculture and food security. Globally the saline front has encroached more than 100 km inland into ponds, groundwater systems, and agro-ecological lan ds through various estuaries and water inlets connected and interlinked with the major rivers and river systems (Rahman et al., 2020). As a result, the local production system changed; Bangladesh could not escape this global phenomenon.

Mixed Rice-Shrimp Culture in Assasuni

The Assasuni sub-district has some essential features for transforming farmland into aquaculture. The main crops were previously rice, which was represented by the satellite imagery from 1972; however, aquaculture and integrated rice-shrimp farms have replaced traditional rice production with time. Currently, shrimp-based aquaculture dominates most of the Assasuni area. During the monsoon season (July-August), the salinity level in the area is reduced so farmers can transplant *Aman rice* (rainfed) seedlings into the fields, and, by November, the rice is mature, which is demonstrated by the 4,533 ha (10% of the total area) of paddy field (Table 1 and Fig. 2). The following aquaculture farming area was 18,244 ha (47% of the total area) in the post-monsoon season (November).

Boro rice cultivation is reduced to 2,657 ha (5% of the total area), as high soil salinity prevents paddy rice growth and development in the dry season. However, fields that have irrigation facilities can successfully cultivate Paddy rice, regardless of the season. Aquaculture is also decreased as water availability is reduced and falls to 17,895 (42% of the total area).

Paddy rice production in Kalapara

Kalapara was selected for the country's central part, where landmass formation and erosion are more prevalent than other parts of the coastal area. Historically, the land use pattern for this sub-district has not changed much. As most of the land is low lying, long-term inundation is a common challenge, resulting in a lower cropping intensity than the national average. During 2016, the *Aman* rice cultivation area was 28,512 ha (60% of the total area) (Table 1 and Fig. 3). Shrimp farming is not an effective land use here. The remaining area includes a homestead, mangrove forest, and fallow land. Being a low-lying area, deepwater rice (landrace) is widely adopted. Due to salinity (SI Fig. 1)during the dry season, most of the croplands are fallow (Krupnik et al., 2017).

Kalapara farmers previously grew the landrace Aman rice cultivar, which is taller than conventional rice varieties and can withstand submergence. Still, farmers are growing those landraces (Jahan et al., 2020).

Mixed rice-shrimp-salt panning in Chakaria

In Chakaria, the mangrove forest was once a vital feature of the eastern coast (Fig. 4, left). Satellite images also show that, in 1972, salt panning was the main economic activity around the mangroves, along with sporadic shrimp farming. After 1972, the mangroves' deforestation became an issue, though a strip of mangrove forest existed until 1990 (Iftekhar and Islam, 2004). After 1972, Chakaria's residents were attracted to aquaculture due to its high return on investment, and it gradually overtook traditional rice farming as the preferred method in the area (Islam et al., 2019). In the post-monsoon period of 2016, the land dedicated to aquaculture farming encompassed 12,235 ha (12% of the area), while traditional cropland covered just 2,526 ha (2% of the area). The wet season in Chakaria is not suitable for evaporative salt production, so land use for salt panning was not calculated. During the February monsoon season, land used for aquaculture area was reduced to 6,977 ha (7% of the area), cropland was 3,116 ha (3% of the area), and the salt panning area as 5,856 (6% of the area).

Blended fresh and saline-based production system

Paddy rice is a staple crop, and widely grown in Bangladesh. It is grown during three annual seasons (pre-monsoon - *Aus rice*, monsoon - *Aman rice*, and post-monsoon - *Boro rice*). The coastal areas of Bangladesh have high spatial and temporal diversities in rice production (Jahan et al., 2020). The western, central, and eastern areas show distinct rice production features due to their different biogeophysical characteristics. In Assasuni, most of the rice farmers grow high-yielding varieties, which are short in stature. In the area, salinity and submergence are not the main concerns during the monsoon season. Plant heights are moderate and range from 80–130 cm, whereas in Kalapara, the plants may reach 170 cm (Table 2). This height difference is due to the submergence-tolerance characteristics of the crop grown in the low-lying areas. In Chakaria, plant heights are moderate and vary from 80–120 cm; the varieties grown are mostly modern paddy rice varieties like BRRI Dhan 28, BRRI Dhan 33.

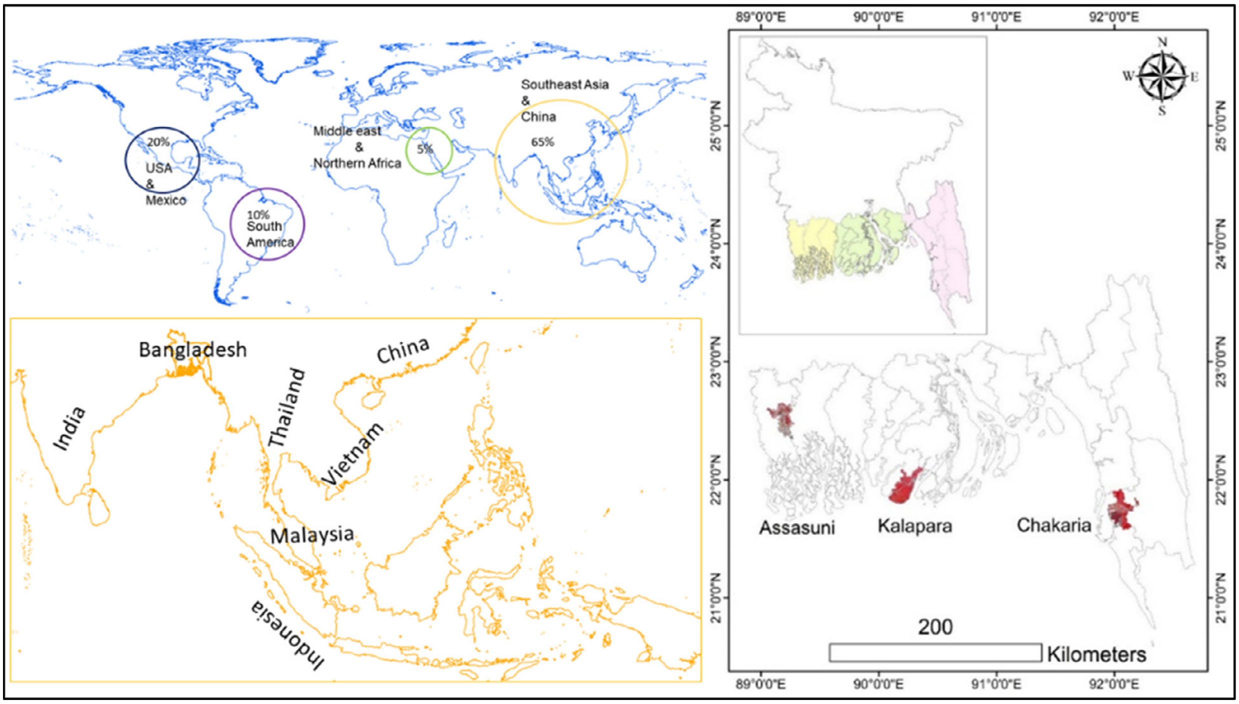

Fig. 1. Global coastal map (a) showing major shrimp producing area and their contribution (% production). Map (b) showing the major shrimp producer in south-east Asia. Map (c) of the Bangladesh coast representing the three sub-districts Assasuni (west), Kalapara (middle), and Chakaria (east) as a representative of a diversified coastal production system.

Table 2
Commonly grown rice varieties and their characteristics as adapted to coastal Bangladesh (based on our survey n = 310)

Descriptor	Assasuni	Kalapara	Chakaria
Name of commonly grown paddy rice variety	*BRRI dhan28* *Basmati* *Guti Swarna* *Jamaibabu* *Jamaibabu Sada* *Minikit Chikon*	*Sada Mota* *Lal Mota* *Motha Mota* *Kuti Agrahayoni* *Kajol Shail* *Kacha Mota*	*BRRI dhan28* *BRRI dhan33*
Yield	High Yielding Variety (fine grain)	Land Race (local) (coarse grain)	High Yielding Variety (fine grain)
Plant height (cm)	80–130	160–170	80–120
Special characteristics	Prone to submergence	Submergence tolerant	Prone to submergence
Growing season	Mainly monsoon	Monsoon only	Pre-monsoon with some monsoon (sporadic)

Fig. 5 shows the inconsistent pattern of salt production in Bangladesh from 2001 to 2018, but the last two-year trend shows a definite increase in production. Both total production output and area utilized for production have increased since 2001. This is due to saline water availability/sea level rise. Shrimp production has also experienced a stable increase rate since 2001, with a 200% production increase from 2001 to 2018. The area under shrimp cultivation also increased from 2001 to 2011 before reaching a plateau. In the last two years, the area used for shrimp cultivation has decreased, despite the production was an increase. Rice production has also increased since 2001, and overall production has increased by approximately 150% as of 2018, despite the size of the area under cultivation not increasing at the same rate. These production increases with stable or decreasing paddy rice based land use are because of integrated rice-shrimp farming increased rice and shrimp production on the same plot of land. Besides, while shrimp exports show a steady decrease in levels since 2014, but crab production has experienced a significant expansion in recent years (BBS, 2019). Overall, crab exports increased by approximately 500% between 2011 and 2018 (BBS, 2019; Rahman et al., 2020). This trend justifies farmers' decisions to change from shrimp to crab farming or utilize a method that integrates both farming.

Continuous Change Detection and Classification (CCDC) based change detection

Time series of NDVI data were fitted using CCDC algorithm. It showed the changes in NDVI pattern over the time (Fig. 6). In Assasuni, major shift from rice to shrimp was detected during 1994. While in Kalapara rice monoculture is visible without any major shift. However, in Chakaria, three definite break is visible.

4. Discussion

In many global coast monocultures without diversity cause socioecological challenges for the communities (Morshed et al., 2020; Silverman et al., 2019). The coastal communities in Bangladesh have developed a dynamic production system that ensures livelihood to the coastal communities. In Assasuni, Kalapara, and Chakaria, land under paddy rice cultivation was 4,533 (12%), 28,512 (59%), and 2,526 (2%) hectares (ha), respectively, which was further reduced during the dry season (Figs 2, 3 and 4) due to salinity rise (Islam et al., 2020; Dasgupta et al., 2018). Salt production in Chakaria took place during the dry season only, utilizing 5,856 ha (6%). In Assasuni and Chakaria, aquaculture areas encompassed 18,244 (48%) and 12,235 (12%) ha, respectively in the monsoon, and during pre-monsoon, the aquaculture area was further reduced to 17,895 (47%) and 6,977 (7%) ha, respectively, due to decreased availability of water. Shrimp dominated, occasional paddy field (west coast), paddy rice dominated (mid-coast), and salt-aquaculture-paddy rice mixed (east coast) is the salient feature of coastal transformation in Bangladesh.

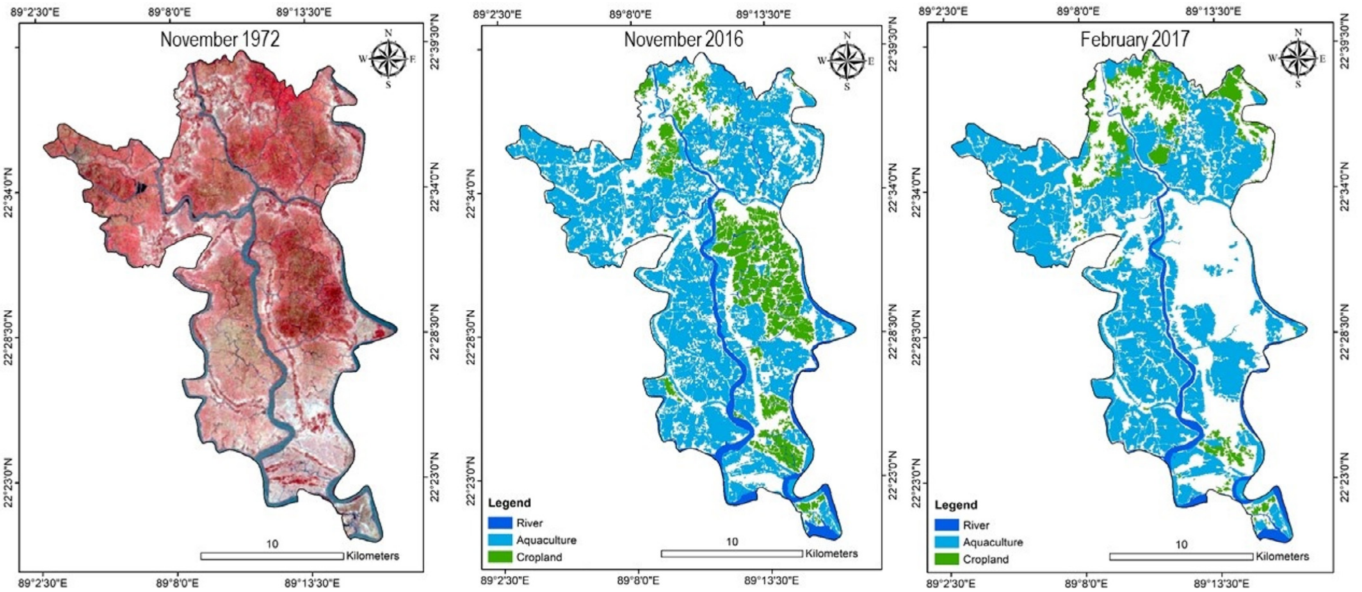

Fig. 2. Shows the base map (left) and recent spatial-temporal changes to major land use of the Assasuni sub-district (center, right) from November 1972 to February 2017. A considerable conversion of cropland to aquaculture gradually took place due to salinity and sea-level rise related saline water intrusion. During dry season many of the croplands are remains fallow. Still, the coexistence of rice and shrimp ensures food security.

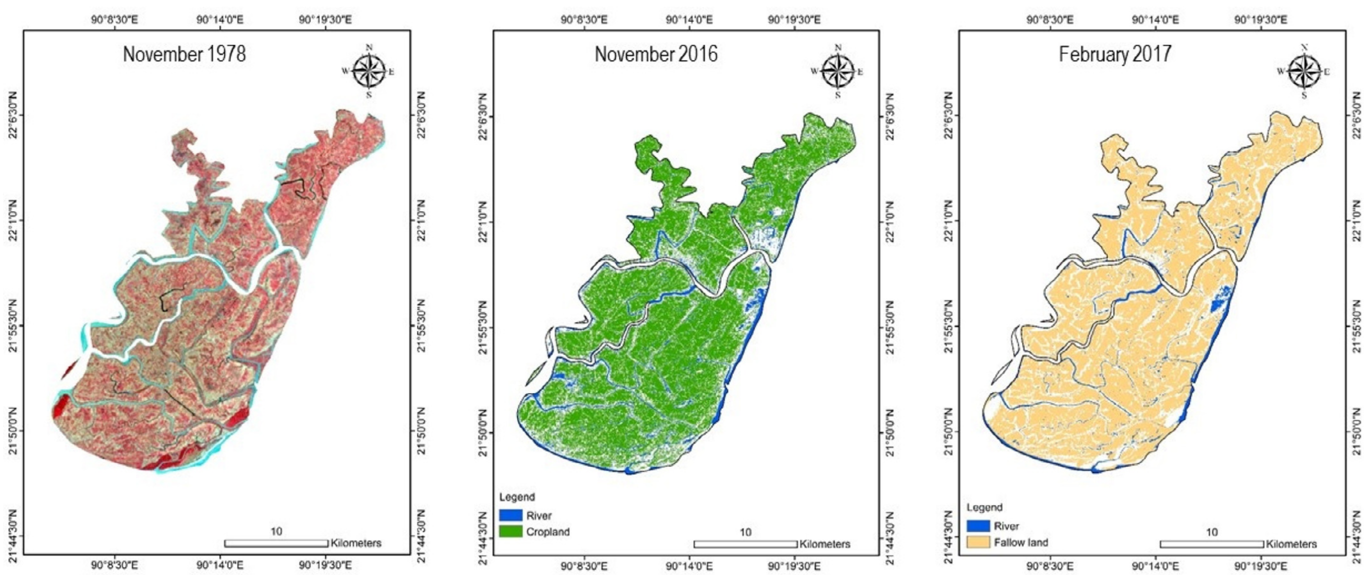

Fig. 3. Shows the base map (left) and recent spatial-temporal changes of major land utilization category of the Kalapara sub-district (center, right). Due to the area's salinity, only *Aman* rice (wet season) is grown.

For the past few decades, climate change impacts on coastal areas have become prominent, for instance sea level rise causing saline intrusion to the mainland (Lenzen et al., 2019). To aggravate the situation frequent storm surge caused by cyclone, tsunami, hurricane bringing more salinity on the shore. Along with the natural forces, various anthropogenic causes like dams' construction, intensive shrimp farming make the situation worse (Morshed et al., 2020; Jayanthi et al., 2018). Around 58,000 larger dams and 16 million smaller impoundments are built worldwide, resulting in reduced river flow and caused sedimentation in the river (Mulligan et al., 2020). The reduction of sweet water discharge is allowing brackish water to invade inland. This blending of saline water is getting accelerated by intensive shrimp farming. Due to high demand and profitability, farmers are adopting shrimp culture over traditional farming practices (Blythe et al., 2015). Thus they are pumping brackish water in the shrimp pond. Usually, it takes 120-140 days for a shrimp to grow at its marketable size. This prolonged entrapment of brackish water gradually increases the salinity of the surroundings. As the salinity increase, more and more land becomes ill-suited for traditional farming, and farmers are left with no choice to convert their cropland to a shrimp farm(Pokrant, 2014). With the continuity of the cycle, more and more areas get dominated by saline water.

Though shrimp farming has a substantial economic return, this practice is not always ecologically and environmentally viable (Boone et al., 2017; Afroz et al., 2017). Once anthropogenic salinization occurs at a certain place, it cannot be undone, which leaves permanent damage to that place (Islam and Tabeta, 2019). In most cases, salinity occurs in the paddy rice field that gets converted into a shrimp farming pond. The reduction of rice farming land results in potential food insecurity.

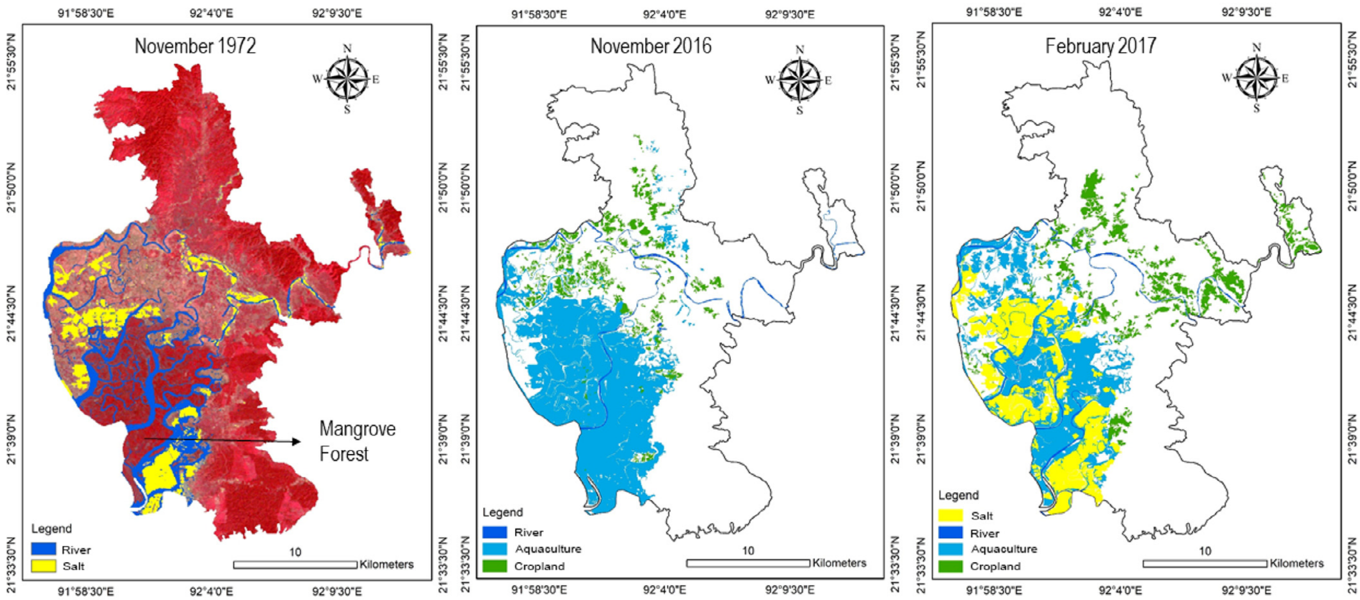

Fig. 4. Demonstrates the salt pan (left) overlaid on the base map and recent spatial-temporal changes of major land use category of the Chakaria sub-district (center, right). The mangrove forest is encroached upon by aquaculture and salt production.

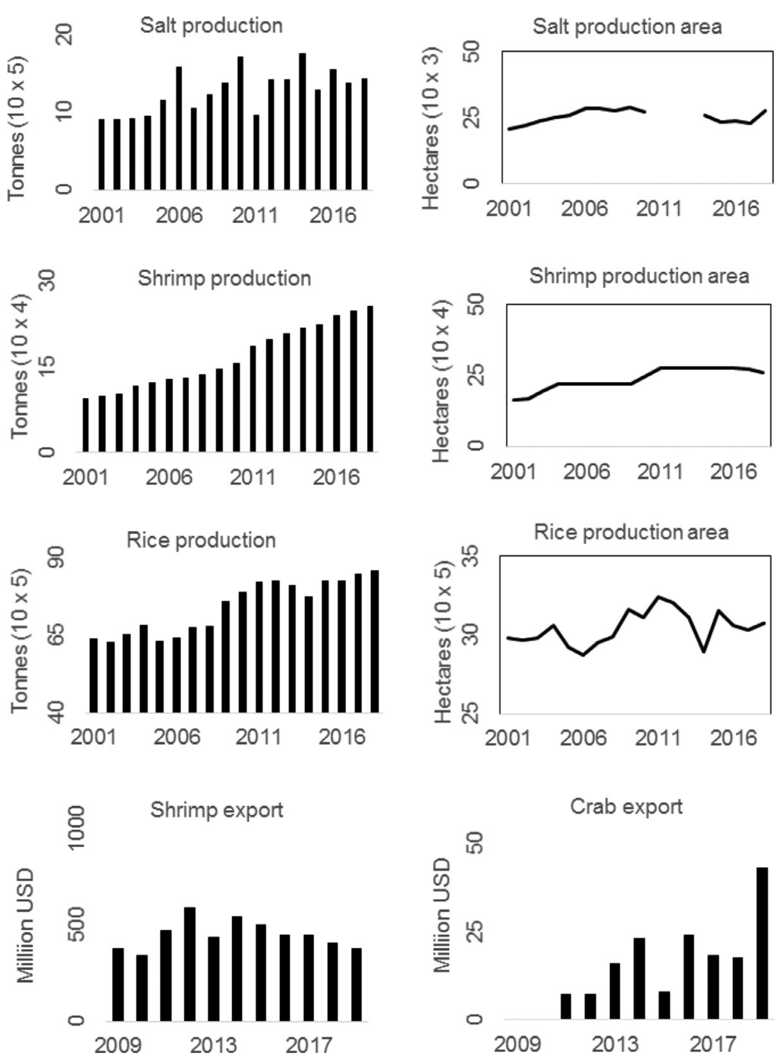

Fig. 5. Shows the trend of livelihood division among salt, shrimp, and rice production and shrimp and crab exporting in coastal Bangladesh (BBS, 2019)

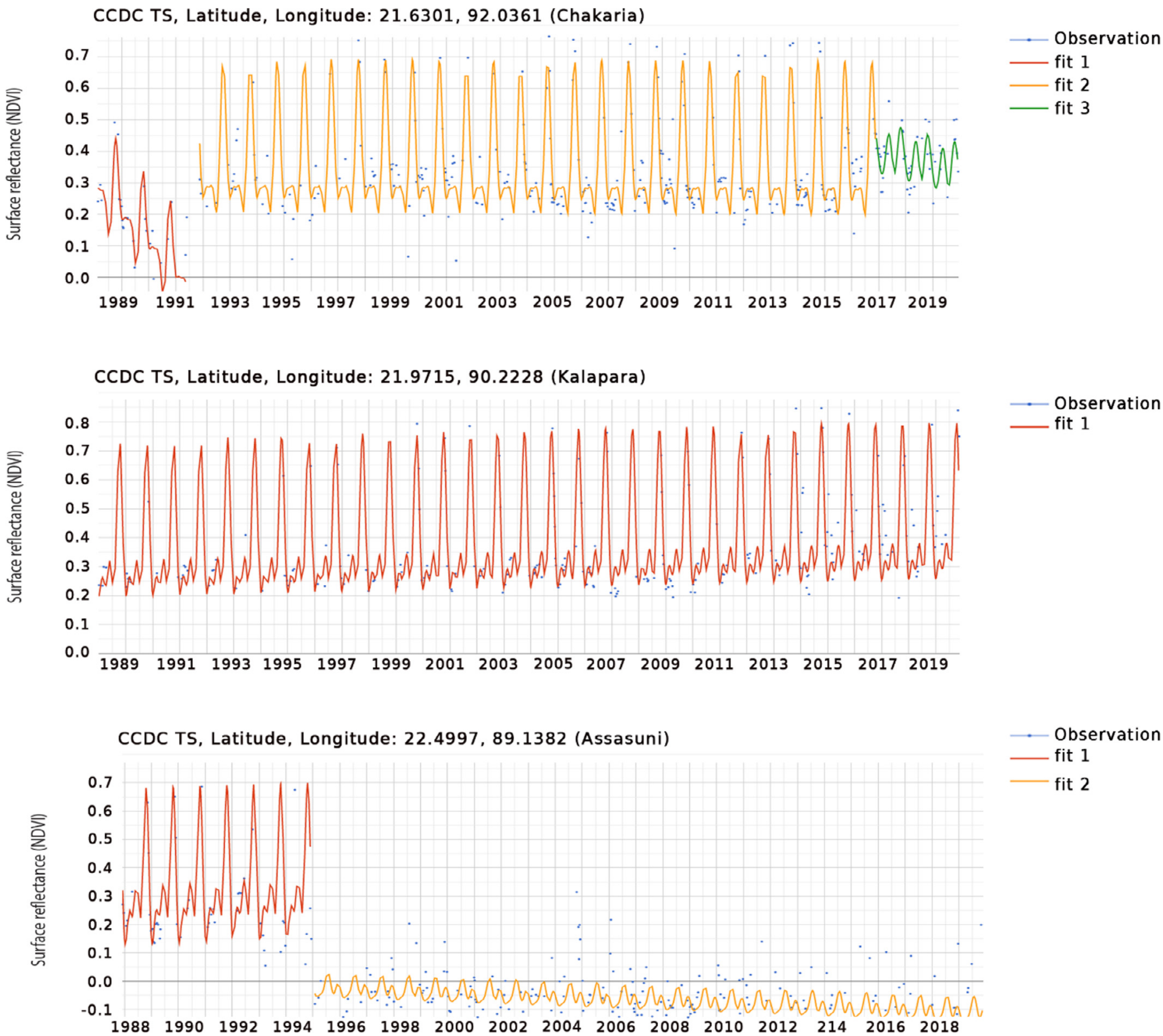

Fig. 6. Continuous Change Detection and Classification (CCDC) algorithm based model fit of normalized difference vegetation index (NDVI) showing the example shift of land use change in three study sites.

That's why inclusive farming (mixed cropping) is necessary to ensure food security.

Moreover, the shrimp production cost is much higher than the rice cultivation. So, production failure in case of a disease outbreak makes the process a risky venture(Valderrama et al., 2017). Besides, shrimp monoculture has some disadvantages no one can ignore. Disease and pest outbreaks, high risk, environmental damage are positively associated with monoculture farming practice(Silverman et al., 2019). However, this unwanted loss can be avoided if inclusive farming is practiced. As the population is increasing day by day, demand for staple food is also increasing. In this situation, more cropland conversion to shrimp farms will put a burden on crop production. Thus to ensure food security coexistence of both crop and shrimp is a must. Goverment initiative regading coastal agriculture is now a critical issue. Only strong regulatory monitoring and policy implementiation could prevent coastal land conversion. Thus it can ensure blended coastal production system in the coast.

5. Conclusion

Agriculture and fisheries production in a regional blending can provide valuable information when developing a solution for the coastal sustainability studies and be useful for policymakers at national and regional levels. Coastal hazards and land-management practices are leading to a situation where long-term cropping practices are transforming. The paper highlighted the causes of progressive salinization related to the coast's socioecological challenges and how production practices are changed over time. The study illustrates the need for both fresh and saline water production system. Production diversification gives communities a wide choice to produce. Simultaneously, it reminds us of the coexistence of fresh and saline water production systems is a key to reconcile the negative impacts of shrimp monoculture. Each coast has spatial and temporal challenges, and successful adaptation to those challenges is critical to the coastal transformation and sustainability.

Declaration of Competing Interest

None

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2021.100089.

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