Ecological Processes

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# Assessing effectiveness of nature-based solution with big earth data: 60 years mangrove plantation program in Bangladesh coast

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## Abstract

**Background** In the climate change context, nature-based solution (NBS) is considered one of the effective tools to increase the resilience of socio-ecological system. The concept coincides with the government's attempts of afforestation and reforestation programs that have been going on for 60 years in Bangladesh. This study, therefore, envisaged understanding how NBS (mangrove afforestation and reforestation) works to promote climate change resilience through the synthetization of remote sensing-based big earth data, statistical tools, and models. The study took the entire coast of Bangladesh except for Sundarbans Reserve Forest and rolled back to 1962 to work on 60 years' time series data. Declassified CORONA satellite imagery along with Landsat satellite imagery was used, which is the first-ever attempt in the remote sensing-based ecosystem work in Bangladesh.

**Results** The study's main innovation is to spatially establish the effectiveness of the NBS. The study critically assessed and estimated stable lands and their socio-economic benefits as part of the effectiveness of the NBS. As part of the NBS-derived benefits in the context of climate change, it estimated the sequestrated carbon in mangrove forests. A significant positive relationship was observed between the increase of mangroves and stable lands. Near about 448,011 ha of agricultural land was stabilized due to the NBS intervention whose economic value is 18,837 million USD. In addition, 29,755.71 kt of carbon have been sequestrated due to NBS program.

**Conclusions** The concept of NBS is still in the development stage and very little or no work has been done so far in measuring and labeling the effectiveness of the NBS. Therefore, our study can innovatively contribute to the scientific community to show the effectiveness of the NBS in three domains (social, economic and ecological) in the changing climatic scenario.

**Keywords** Nature-based solution (NBS), Mangrove afforestation program, Coast, Geographic Information System, Remote sensing, CORONA satellite image, Land stabilization, Sequestrated carbon, Climate change

## Background

Bangladesh is situated in a very active geomorphological location as the country is the outlet of one of the world's largest Ganges–Brahmaputra–Meghna Basin (Nishat and Mukherjee 2013). Billion tons of sediments fall into the Bay of Bengal is carried out from the upper riparian countries (i.e., India–Nepal–China) (Roy and Mahmood 2016; Brammer 2012). Rolling back to geological time scale and the history of the Bengal delta, it is found that the formation of the country is the sum of the cumulative stabilization of the sediments over time (Brammer

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2014). Concerning this, it has been observed huge accretion activities in the coasts and estuaries of Bangladesh. However, as the coast of Bangladesh is geomorphologically very dynamic, therefore, in parallel to accretion, it is observed huge events of land erosion (Mahmood et al. 2020). Moreover, as the world is embracing the worst possible situation of climate change which is no longer a hypothetical term but a mere reality, a country like Bangladesh is in imminent threat from climate change-induced natural disasters (IPCC 2019). As the coast of Bangladesh has been going through this complex process of erosion and accretion, the loss of land due to erosion is a great opportunity cost for the country when it is one of densely populated countries and owned only 144,570 $km^2$ of land (BBS 2011). Therefore, parcels of land are very demanding in Bangladesh, especially for cultivation and housing, and the process of erosion always left huge number of people as landless ness (Mahmood and Mahbub 2018; Mahmood 2015).

The loss of arable lands by the smallholding farmers, back-to-back strikes of the climate change-induced natural disasters, exposure to the Bay of Bengal, and fragile socio-economic condition of the marginal community enhance the vulnerabilities of coastal communities in Bangladesh (Mahmood and Mahbub 2018). In fact, based on the vulnerabilities especially the vulnerability of the coastal people, the country has been listed as the 7th most vulnerable country in the world due to climate change (IPCC 2014). However, Bangladesh has a long tradition and experience in disaster management and showed significant character to reduce the loss and damage by its own arrangements. The likelihood of increasing loss and damage due to climate change and environmental degradation (IPCC 2014) leads to the development and adoption of new combating approaches and strategies, i.e., nature-based solutions (NBS). The International Union for Conservation of Nature (IUCN) (Cohen-Shacham et al. 2016) defines NBS as "… actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." This promising approach resembles the role of the ecosystem in reducing climate change impact based on the principle that enhancing and protecting nature, natural features, and natural processes (EC 2015) to ensure sustainable delivery of ecosystem services (ES) and buffering the adverse impacts of climate change (Martin et al. 2020). NBS has been framed as 'an umbrella concept' for ecosystem-based approaches, such as ecosystem-based adaptation (EbA), mitigation (EbM), disaster risk reduction (Eco-DRR), and Green Infrastructure (GI) (Nature Editorial 2017) and embedded several conservation and sustainability measures (Cohen-Shacham et al. 2016; Maes and Jacobs 2017; Eggermont et al. 2015). It mainly highlights the role of ecosystem functions and processes for long-term sustainability as a part of adaptation strategies to climate change. NBS enhances the capability of social–ecological systems to cope with risks by exploiting the intrinsic resilience of natural processes (Mahmood et al. 2021; Martin et al. 2020) and requires engagement with multiple actors, providing co-benefits that bridge social and economic interests and as thus, offers a realistic transition path towards a sustainable economy (Maes and Jacobs 2017) stimulating new green economies and green jobs (Kabisch et al. 2017; Raymond et al. 2017) which makes this concept very valuable to civil society groups, donors, decision-makers, both public and private investors insurers.

Since NBS uses ecosystem function to deliver benefits to society, coastal afforestation has long been considered a viable NBS option for climate change adaptation (DoE 2015). It links adaptation of an ecosystem that can further influence the mitigation potential (e.g., by sequestering carbon in vegetation), with an overall dramatic increase in resilience (Mahmood et al. 2022; Van den Bergh 2011) to coastal flood, shoreline erosion, cyclone, and related storm surge through bottom friction, the cross-shore width of forests, tree density and shape (Menendez et al. 2020) along with multiple co-benefits such as carbon sequestration, land stabilization, job creation, tourism, etc. For example, afforesting, protecting, and managing mangroves to enhance coastal resilience to multi-hazard vulnerability is an NBS option. Mangrove's forest stabilizes soil by retaining sediments in intertidal areas (Mahmood et al. 2020), dissipates waves and storm surge (Samiksha et al. 2019), and serves as an adaptive defense as they can keep pace with sea level rise through vertical accretion (Krauss et al. 2013). In contrast, any technical adaptation measures such as the establishment of polders to protect coastal settlement are not considered to be an NBS option as they do not use ecosystem function as mangrove afforestation does. Menendez et al. (2020) mentioned that around 90% of the total benefits of mangroves are for tropical cyclone protection that includes the protection of 14 million people along with the reduction of expected flood damages by $US 60 billion annually.

Although the concept of NBS is relatively new, the Government of Bangladesh has long been practicing it through its coastal afforestation and reforestation initiatives since 1965. The aim of the coastal afforestation in the mudflat or intertidal zones is to accelerate the accretion process and help the accreted lands to be stabilized (Mahmood et al. 2020). Bangladesh Forest Department (BFD) under the Ministry of Environment Forest and Climate Change (MoEFCC) is responsible for the afforestation and reforestation program and the maintenance and management of the plantation initiative. The NBS initiative of afforestation and reforestation started in 1965 and at that time other than Sundarban Reserve Forest (SRF) only a few natural patches of mangrove forest existed (e.g., Chakaria Sundarban, Chakaria; Tengragiri, Barguna) in the whole coast of Bangladesh. The toposheet map of 1950 also suggests the status of the coast which is far more different compared to the present status. The recent field observation, secondary literature, and satellite imagery-based observation claim that there have been increased patches of mangrove and coastal lands have also been increased. Although significant changes were observed within the structure and land cover of the coast (e.g., increased amount of mangrove patches, mudflats, agricultural land, etc.), there have been no, or very limited studies conducted on the afforested and reforested mangrove forests. The currently available studies in Bangladesh discretely focused on some of the mangrove patches but again limited only to the land use and land cover information (Hasan et al. 2020; Mahmood and Mahbub 2018). As we reviewed the literature, Al Mamun et al. (2021) strived on valuing the ecosystem services of the Hatiya mangrove forest and showed the economic benefit against timber and accreted land. However, the study has the limitation to establish the relationship between increased mangroves and settled land. The study assumed that the mangrove patches can provide benefits through accreting lands, but the study did not focus on establishing the relationship. Again, its terms of mangrove-based study, some other studies focusing on the small areas, but this study limitedly used remote sensing-based earth observation and hence lacked evidence-based observation and analysis.

In this study, we utilized the opportunity of applying the declassified satellite imagery data that used to be the military intelligence data of the United States. The afforestation initiative started back in 1965 and it is claimed that almost all the coastal mangrove patches (except SRF, Tengragiri, Chakaria Sundarban) are driven by the afforestation program of the Bangladesh Forest Department. Therefore, the declassified CORONA satellite photo carries huge significance in providing information on the coastal structure and morphology before the afforestation program. Although the Landsat satellite mission dates to 1972 and provides influential data to date, it does not have data before 1972. Therefore, the study combines both the CORONA satellite photos and the Landsat mission to assess the NBS initiative. The study envisaged to address the following research questions and objectives: (a) whether the coastal mangrove afforestation and reforestation initiative of Bangladesh has a significant relationship in stabilizing the accreted land into settled and permanent land; (b) what types of ecological, socioeconomic services and benefits that the coastal afforestation–reforestation based initiative brought since its introduction. The study results envisaged evidence-based analysis and mapping to highlight the benefits of the NBS that potentially supports the forest managers and policymakers in taking appropriate future intervention of NBS.

## Methods

### Study area

The study considered the whole coast of Bangladesh where NBS have been intervened from time to time by BFD. The plantation database of BFD suggests that it covered all four afforestation divisions. Therefore, in this assessment of NBS, we considered the whole coast of Bangladesh Except SRF. The SRF is a natural mangrove forest patch and is considered one of the largest single-patch mangrove forests in the world (Hasan et al. 2020). It is claimed that the mangrove that we observe in the coast of Bangladesh is the cumulative NBS exercise of BFD which started back in 1965. Therefore, it is assumed that the implication of afforestation work (NBS) would be very high and there would be no mangrove forests in the study area before the intervention (~1965). In our study area, the *Tengragiri Wildlife Sanctuary* existed before 1965. However, as it has gone through huge changes like it received reforestation activities (DoE 2015), therefore the wildlife sanctuary is included in the study area even though it was originally a natural mangrove forest. Moreover, in Chakaria there used to be another mangrove patch namely *Chakaria Sundarbans* which was also a natural mangrove forests, but disappeared due to illegal shrimp cultivation and severe anthropogenic stresses. Therefore, we also included this patch which is observed in the satellite imageries of the past (1973 Landsat MSS imageries and ~1962 CORONA photos). Since, the patches gone completely disappeared, this has also been discarded from our study area. Administratively, the study area falls within the district administrative units of Patuakhali, Barguna, Bhola, Noakhali, Feni, Chittagong, and Cox's Bazar (BBS 2011). The study area comprises estuaries (*The Meghna*) and many associated riverine char lands. As for the coast (Bay of Bengal) many coastal islands experience severe and dynamic geomorphological processes (Mahmood et al. 2020; Mahmood and Mahbub 2018; Roy and Mahmood 2016; Brammer 2014).

Geographically the study area falls between 22°56′ N, 89°56′ E and 21° 26′ N, 91° 57′ E in the southernmost part of the country (Fig. 1). As the study focuses on the NBS based on the salinity and soil composition, the species distribution also varies across the study area. The western coast (Patuakhali and parts of Bhola) is Keora (*Sonneratia apetala*) and Gewa (*Excoecaria agallocha*) dominant, the central coast is specially Keora dominant with a little mix of Bain (*Avicennia officinalis*); however, the southeast part of the study area is Bain dominant (DoE 2015). Based on the species and their biophysical context, their contribution to ecosystem services also differs.

### Data sources

The study attempted to roll back to the year when there was no afforestation and reforestation (NBS) program, so that an effective baseline status can be known. However, there was no spatial data on afforestation and reforestation work except for some ancillary data from plantation records. Therefore, the study required to rely on remotely sensed satellite imagery to assess the status of the coast before 1965. However, there we encountered the challenge of data limitation as the well-known Landsat series has historical data only from 1973. However, an opportunity opened as the United States declassified CORONA satellite imagery that dates to 1960. The CORONA used to take photos from the military satellite and the spatial resolution, in general, is as good as ~ 3 m. The CORONA satellite photo is a single-band panchromatic image and is available to download from the USGS Earth Explorer site (https://earthexplorer.usgs.gov). The data are available to download through two modalities. There are some scenes that are immediately available to download, but there are other scenes that are required to order and become available after payment. The study collected CORONA satellite imagery through the combination of both procedures and prepared to use for the analysis.

The Landsat satellite mission is a very well-own and very effective mid-resolution satellite imagery that serving the scientific community for 50 years through various missions. In the case of our study, we used the Landsat series from 1973 to 2021 which comprises Landsat-3, 4; Landsat 5, Landsat 7, and Landsat 8. Altogether 6 Landsat imageries were prepared from 24 Landsat scenes as required by the study area. The study considered 1973, 1980, 1990, 2000, 2011, and 2021 years maintaining ~ 10 years period to investigate the changes in planted mangroves and other associated land cover and land uses. The USGS Earth Explorer site (https://earthexplorer.usgs.gov) has the data repository for all Landsat series, but as the study employed the cloud-based Google Earth Engine (GEE) platform the imageries were prepared and processed through the GEE.

The study collected different GIS layers (e.g., administrative boundaries, BFD boundaries, and some recent plantation parcel layers) from different government agencies and organizations. The biomass data were collected from Bangladesh Forest Inventory (BFI) (http://bfis.bforest.gov.bd/bfi) prepared by Bangladesh Forest Department. The land price information has been collected from local people to get the contemporary market price through field survey (Table 1).

### Data preparation and image classification

#### *Data preparation*

The study used CORONA and Landsat satellite data. However, as we used the Google Earth Engine platform no additional data preparation steps were required prior to image classification (e.g., geometric correction, atmospheric correction, etc.) for Landsat imageries. The Google Earth Engine platform has already processed Top of Atmosphere (TOA) data which can be easily imported as required for any study and exercise. However, the CORONA satellite photos are single-band panchromatic photos, and these data are not geometrically corrected. The study area required nearly 40 image scenes to cover the whole area, and all needed to be geometrically corrected. The geometric correction of the CORONA required rigorous effort as the imagery time was more than 60 years. The study used Landsat 3 imageries which are closest to the year of CORONA photos (~ 1962). At first, the team identified common features (permanent) between the two imageries (e.g., settlement, ponds, building, etc.) and attempted to rectify the image by applying 2 order polynomial rectification through Erdas Imagine 2014 platform. All the CORONA imageries have been geometrically corrected following this method and finally mosaiced with the study area boundary to form a single image of the study area. The CORONA satellite imageries along with all other satellite images and geospatial layers have been projected to Universal Transverse Mercator (UTM) with 46 N zone (Hasan et al. 2020) (Fig. 2).

In the case of land price data, the data were collected from the https://www.dolil.com/market-value/ website. The data have been recorded here as per the cadastral boundary. It means, in each cadastral jurisdiction, the price of land differs. It is to be noted that only agricultural lands have been considered here. At first, the data have been recorded against the mouza boundary of the study areas and then data have been extrapolated to a 5 km × 5 km grid where it is assumed to quantify the land price (Fig. 3). Once we have recorded the data against the grid, we have visualized the data by 5 classes, and we visited 10 sites to observe and validate the land price. In Bangladesh, generally, the cadastral price (mouza) is always 2 to 3 times less than the market price as people tend to show the low prices during the purchase of land. However, during our field survey, we found that this trend is true, and the price recorded on the website matches the local sub-register office prices. Although

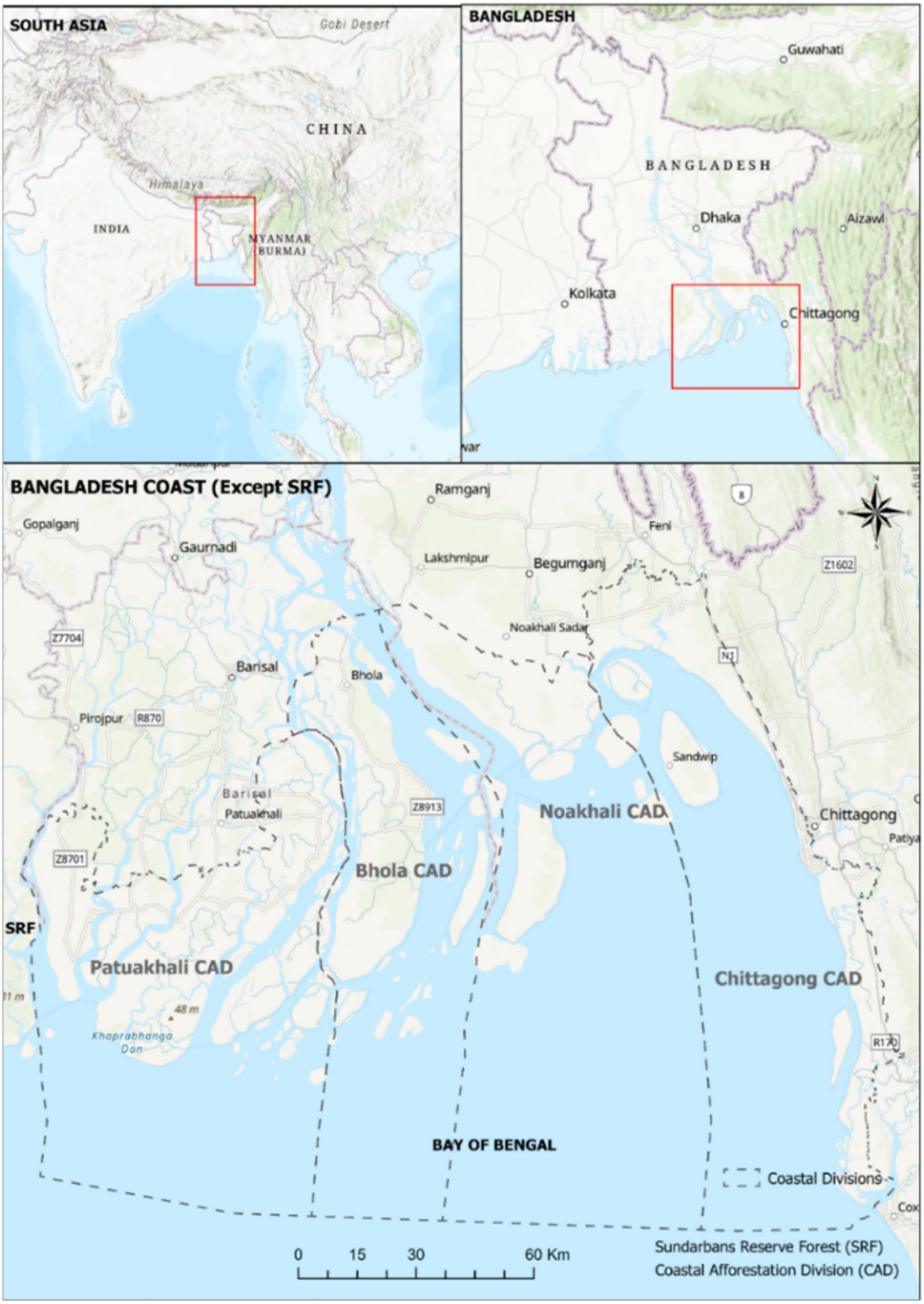


**Fig. 1** Coast of Bangladesh except for Sundarbans Reserve Forest (SRF). The grey dashed lines represent four Coastal Afforestation Divisions (CAD) of the country under the jurisdiction of the Bangladesh Forest Department (BFD)

**Table 1** Data sources

| Data type | Year | Spatial resolution | Source |
|---|---|---|---|
| CORONA declassified data | 1962–1965 | ~5 m | https://earthexplorer.usgs.gov |
| Landsat 3 (MSS) | 1973 | 60 m | USGS/Google (https://landsat.usgs.gov/) |
| Landsat 4 (MSS) | 1980 | | |
| Landsat 5 TM | 1990 | 30 m | |
| | 2011 | | |
| Landsat 7 (ETM) | 2000 | | |
| Landsat 8 (OLI) | 2021 | | |
| Google Earth images | 2000–2021 | ~2 m | Google Earth Pro, Google Earth Engine (GEE) |
| National Administrative Boundary | NA | NA | Survey of Bangladesh |
| Coastal Afforestation Division Boundary | 2015 | NA | Bangladesh Forest Department |
| Coastal plantation layer | 2015 | NA | |
| Mangrove biomass data | 2020 | ha | Bangladesh Forest Department (http://bfis.bforest.gov.bd/bfi) |
| Land price data | 2021 | NA | Field Survey Data, Land Office (https://www.dolil.com/market-value) |


**Fig. 2** Processed CORONA satellite imagery and Landsat satellite imageries

the registered (official) value of the land is almost two times lower than the market price, the study considered the official price. As for easy understanding and universalities, the land price has been converted into US Dollars (USD) based on the current exchange rate (January 2022).

In the case of biomass estimation as part of the ecological benefits, we need to find out the biomass amount per unit of planted mangroves or mangrove forests. We relied on secondary sources as the scope of the study does not permit to establish plots and estimating the biomass quantity per unit. Bangladesh Forest Department is the sole authority to conduct afforestation and under BFD, a countrywide forest inventory has been conducted with financial and technical support from the United States Agency for International Development (USAID) and the Food and Agriculture Organization (FAO), respectively. The findings of the Bangladesh Forest Inventory (BFI) have been recorded (Table 2) and were used for the calculation of the biomass and carbon as part of the

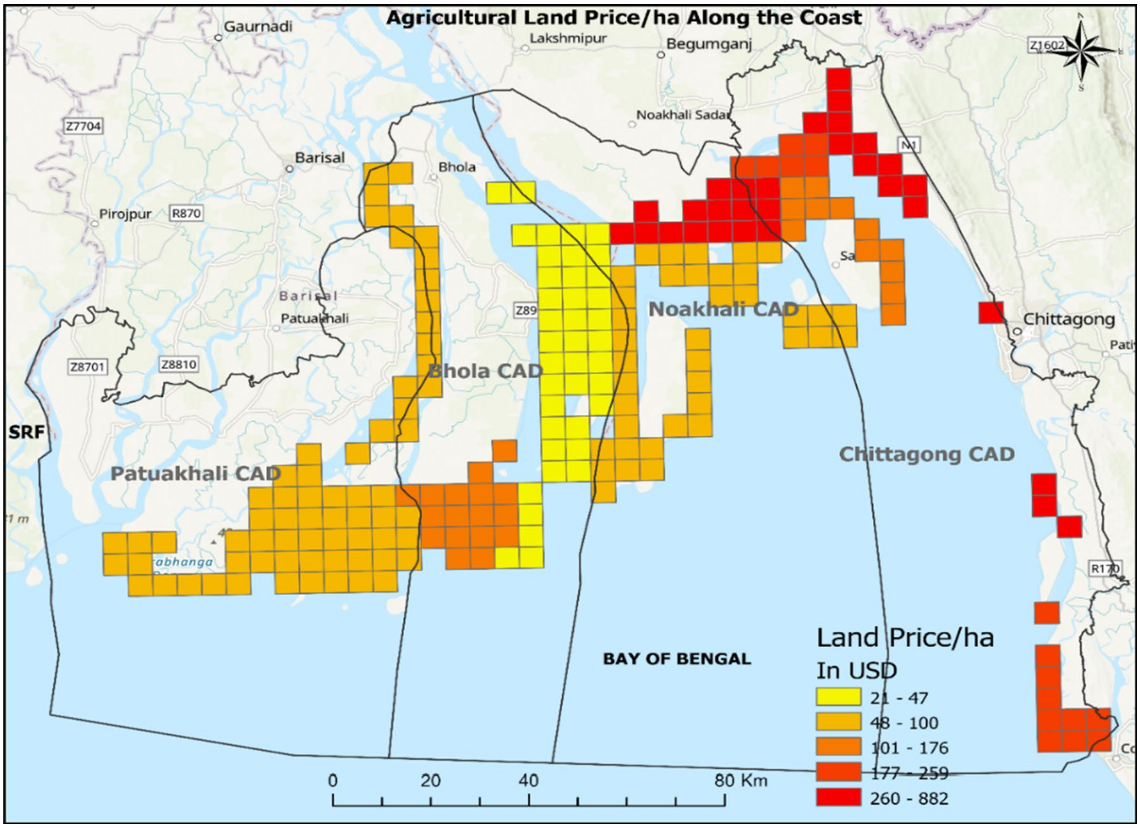


**Fig. 3** Distribution of agricultural land price across the coast

**Table 2** Amount of biomass per hectare of mangrove forests for both planted and natural mangrove forests in the coastal zone of Bangladesh)

| SL | Carbon pool | Planted mangroves (ton/ha) | Natural mangroves (ton/ha) | Min (ton/ha) | Max (ton/ha) |
|---|---|---|---|---|---|
| 1 | AGB | 74.6 | 98.34 | 0.03 (intertidal area) | 98.34 (natural mangrove forest |
| 2 | Deadwood biomass | 3.49 | 2.28 | 0.03 (herbs dominated area) | 5.16 (hill forests) |
| 3 | Soil carbon (30 cm) | 73.84 | 78.68 | 14.35 (sand) | 153.60 (bamboo forest) |
| 4 | Litter | 0.05 | 0.05 | 0.03 (village) | 0.25 (hill forest) |
| 5 | BGB | 4.15 | 4.15 | 1.99 (village) | 33.03 (Sundarbans) |
| | Total | 156.13 | 183.5 | | |

mangrove-derived ecological benefits. As the content of biomass and carbon varies widely based on multiple criteria (e.g., location, forest structure, species composition, soil composition, etc.), the BFI considered 3 zone-specific allometric equations (i.e., Hill, Sal, and Sundarbans). Sundarbans is the zone for mangroves, therefore BFI considered values of 5 carbon pools (Table 2) under this zone. Furthermore, the forest inventory considered 22 land cover classes across the country to estimate the biomass and carbon, and for our study we considered the planted mangrove class and natural mangrove class. The BFI applied various methods and techniques to derive the value of the carbon under 5 carbon pools based on the field survey data collected from 2015 to 2019.

#### Image classification: CORONA and Landsat imageries

Based on our collection of satellite data, the study considered the classification into two parts. The first part involves the offline application-based classification as the CORONA satellite imagery is not present in the Google Earth Engine archive. The study applied Erdas Imagine application software to classify the CORONA satellite

**Table 3** The classification scheme for land use and land cover for the study area

| LULC types | Description |
|---|---|
| Waterbodies (WB) | Sea, estuaries, rivers, ponds, lakes |
| Mangrove forests (MG) | Mangroves that comprise both natural and planted |
| Homestead vegetation (HV) | Households, settlements, trees, buildings, and other concrete structures |
| Agriculture (AC) | Croplands, bare lands, paddy fields with seasonal water |
| Mudflat (MF) | Wet soil and sediments in the intertidal zone that is totally exposed |
| Sand (SA) | Sandy soil, totally expose |
| Mudflat with grass (MFG) | Wet soil with grass in the intertidal zone of the coast |
| Shrimp culture (SC) | Blocks of water with grid patterns especially located on East Coast |

imageries to find the land use and land cover of ~ 1962. As for the Landsat imageries for 6 years, the study used the GEE platform to classify. However, before classification, it is a prerequisite to determine land use and land cover (LULC) classes. The Anderson classification scheme, Anderson level 1 land use and landcover is a common and widely used method (Anderson et al. 1976) and the study used the modified version of the classification scheme (Hasan et al. 2020; Hasan et al. 2021) to classify the entire coast of Bangladesh. The study carefully examined the satellite imageries and incorporated the field knowledge of the analyst to determine 8 land use and land cover categories for the study. The criteria of a pixel to fall under a specific land use and land cover class are also described and clarified (Table 3).

The study used a hybrid approach to classify the CORONA satellite imageries (Bauer et al. 1994). At first, an Iterative Self-Organizing Data Analysis (ISODATA) algorithm was applied to classify the image by algorithm-specific spectral ranges. The study used Erdas Imagine 2014 platform to classify the CORONA satellite image into 36 classes initially. Later, considering the practical and field knowledge of the analyst, these 36 classes were reclassed into the study-specific 8 classes (Table 3) through reconfiguring attribute tables. The practice is called unsupervised classification and there remain misclassifications and overlaps among classes. As the study considered a hybrid classification approach, the signatures have been collected from this unsupervised data that best matched with the real features, which are then examined carefully using the histogram and Transform Divergence (TD) method (Yuan et al. 2005). The study accepted training data that have a TD value equals to or more than 1900 (Hasan et al. 2021). Besides, as for guiding the training data, multispectral Landsat 3 imageries were also considered for reference to confirm the effectiveness of the training data. A Random Forest (RF) classification algorithm was used through ArcGIS Pro to finally classify the image into our identified and selected classification scheme of 8 LULC classes. The study area is large, and the character of the features is very heterogenous, therefore there occurred misclassification (Hasan et al. 2020). Several post-classification operations were applied to the primarily classified thematic layers to finalize the classification process. To evaluate the classification accuracy, 100 points for each of the classes have been extracted and compared with the reference images (Landsat 3 imageries of 1973 and beyond). As the CORONA satellite image is very old and underwent huge LULC changes, the process was challenging and required time to find out the common and comparable features. Utilizing reference data and points from classified images, an error matrix was prepared to compute four accuracy metrics (i.e., overall, producers, user's accuracies, and kappa statistics).

In order to classify our remaining six sets of Landsat satellite imageries, the study has used the cloud computing-based Google Earth Engine (GEE) platform where temporal aggregation can be attained as mean and median thus to achieve accurate and precise LULC classification quickly and easily compared to the conventional method (Phan et al. 2020). The application of GEE is advantageous as pre-processed datasets are available there and all the processes can be done through a single script. Moreover, the GEE platform helps to avoid the complexity of data downloading, pre-processing and data storage on the local computer. The process is easy in terms of exploring and exercising different methods and techniques as part of the trial and error avoiding data maintenance, especially data cleaning. In our case, 4 scenes are required to cover the whole study area, and to accommodate temporal aggregation we used the mean value of the all-cloud-free scenes of the year 1973 (for Landsat-3), 1980 (for Landsat-4), 1990 (for Landsat-5), 2000 (for Landsat-7), 2011 (for Landsat-5), and 2021 (for Landsat-8) (Phan et al. 2020). The combination of collected training data from the field and the high-resolution background satellite data of GEE was used to generate training sample data for eight LULC classes, which is a widely accepted approach (Hasan et al., 2020; Sousa et al. 2020). We employed the widely used Random Forest (RF) classifier algorithm to classify the six years Landsat data (Li et al. 2016; Amani et al. 2019; Jin et al. 2018) as it easily handles noisier datasets, provides good performance and accuracy. The accuracy of the classification exercise was assessed based on the widely used kappa coefficient (Phan et al. 2020) through the combination of the classified random points and the reference points and the accuracy of the classification was 0.95 and 0.91 for 2021 and 1989, respectively.

#### Assessment of the effectiveness of the NBS program

At first, the study was designed to tabulate the LULC data of all 7 years starting from 1962 to 2021 and applied a correlation matrix to observe whether there is any significant relationship between a mangrove forests and stabilized land use (e.g., agriculture and settlement). However, even though we find a strong relationship between the mangroves forest and stabilized land use, it is important to determine small-scale status of the influence of the mangrove forests. Therefore, the study subtracted the stabilized land of 1962 (baseline year) from the study area to assess the influence of the afforestation in stabilizing the lands. With the subtracted study area, the study created a 1 km × 1 km grid (Fig. 4) and tabulate LULC information for each of the 1 km × 1 km grids for all 7 years (1962–2021). There were 6818 grids in total for each of the years and in total there were 47,726 grids for all 7 years combined. Based on the structure of the database (time series) the study applied panel data regression to assess the effectiveness of the afforestation and reforestation-based nature-based solutions. As the decrease of the waterbodies influences the increase of the land area (e.g., stabilized area), it has been considered as one of the independent variables. Moreover, mudflat is the place where mangroves are planted, and if the mangrove increases it is assumed that the mudflat would also increase. Finally, as the years pass by land use and the land cover gets changed, therefore, alongside planted mangrove forests, the study considered waterbodies (WB), mudflat (MF), and years as the independent variable; whereas the study considered agricultural lands as the stabilized land and hence selected as the dependent variable for the study.

#### Quantification of the socio-economic benefits of NBS

It assesses the effectiveness of the NBS and if the assessment rejects the null hypothesis, it is established that the afforestation and reforestation of mangrove forests significantly contribute to stabilizing the lands. Therefore, the study subtracts the stabilized land (i.e., agriculture lands) of 1962 from the rest of the six years (i.e., 1973, 1980, 1990, 2000, 2011, and 2021). Through this exercise, the study estimates the net stabilized land that has been brought by the proven effects of the NBS initiative (mangrove afforestation). At this stage, the study employed the collected land price as per the spatial distribution of price and the newly stabilized lands. This exercise envisages providing the total land price of the newly stabilized lands in any grid. The data are then visualized through spatial distribution and cartographic exercise for easy understanding and interpretation.

#### Quantification of the ecological benefits of NBS

The study incorporated the findings from the Bangladesh Forest Inventory prepared by the Government of Bangladesh. The BFI work considered tree species distribution along the coast, wood density database, soil analysis, and tree allometric equation. The allometric equation and its precision (1 and 2) determine the quality of the estimation of the volume, biomass, and carbon (Picard et al. 2012) for any planted mangroves. The BFI explored and reviewed various already established allometric equations and finally selected the following equation to use for the estimation of the tree volumes for the planted mangrove forest:

$$lnYagb = 1.7608 + 2.0077ln(D) + 0.2981ln(H) \tag{1}$$

$$ln(\mathrm{CAGB}) = -2.5035 + 2.0042ln(D) - 0.3188ln(H) \tag{2}$$

where CAGB = Carbon in aboveground biomass; $Y$agb = aboveground biomass in particular tree $Y$; $D$ = diameter at breast height; $H$ = tree height.

The BFI study collected biophysical data from field surveys through plots and utilized the allometric equation to find out the total volume per hectare of mangrove forests. The volume per hectare is then multiplied by the suggested wood density per specific to get the biomass and finally the quantified biomass is divided by two to get the carbon that is stored within the mangrove forest. Besides, the study also considered the belowground biomass and soil biomass through specific methods. The carbon data of all carbon pools have been separately estimated in the BFI study and have been adopted in this study. Finally, the area under the mangrove forest class is multiplied by the per hectare biomass to get the total biomass under each of the 1 km × 1 km grids. The findings are then visualized by location to spatially distribute the ecological benefits derived from the afforestation-based NBS.

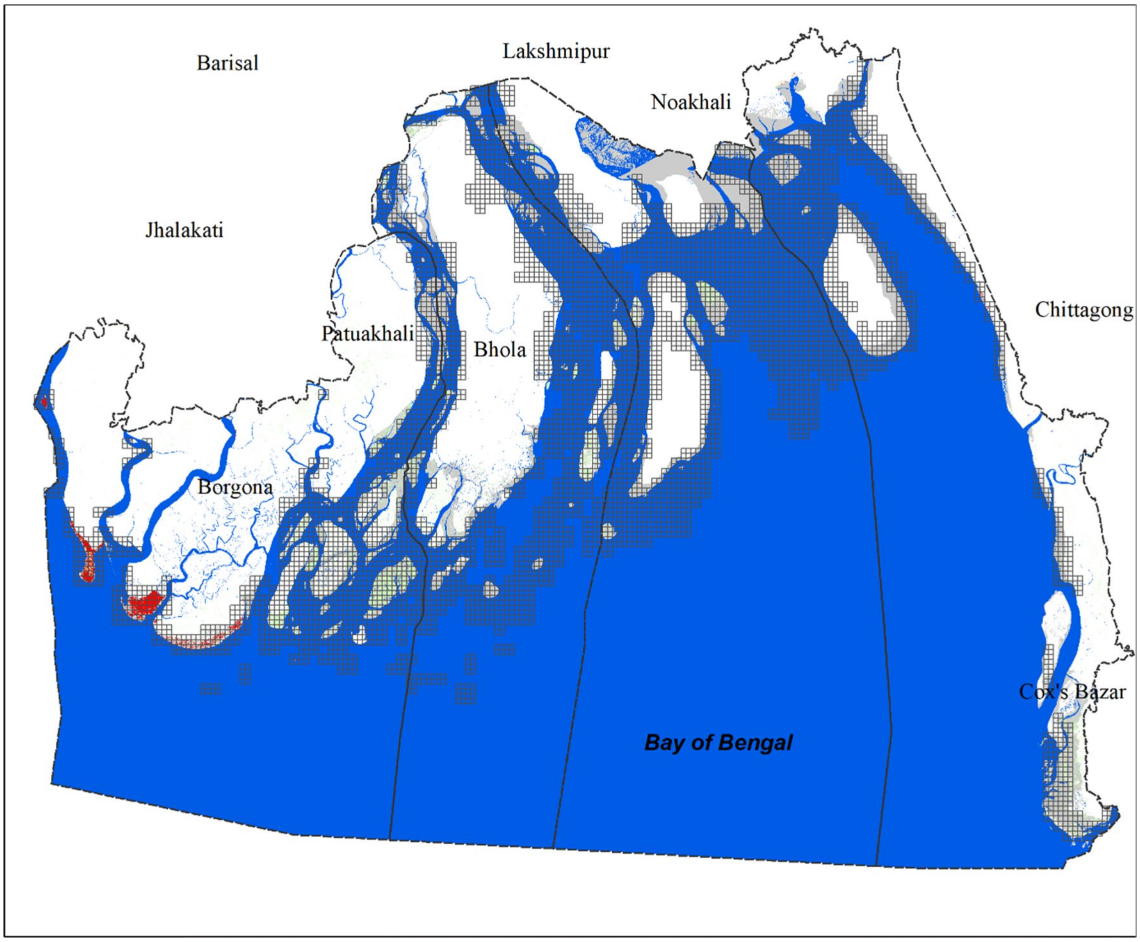


**Fig. 4** Distribution of the 1 km × 1 km grid across the study area. Planted mangroves and mudflats are important factors of the study, therefore, in the area where these land covers are absent, the 1 km × 1 km grid was not considered there

## Results

### Spatio-temporal distribution of NBS and other associated land use and land cover

The study considered 7 temporal years to assess land use and land cover. Since there was no mangrove planted before 1965, we can easily conclude that the mangrove forests that we see on the coast after 1965 are the results of the NBS intervention. However, the Tengragiri patches were there before 1965 marked with a black box in Fig. 5, hence is not considered as the NBS intervention. As can be seen from Fig. 5a, there are only two mangrove patches present in the southwestern corner, but the rest of the area is completely free of planted mangroves. Figure 5a represents the year 1962 and the information is derived from the CORONA satellite imagery. Therefore, 1962 has been considered as the baseline year for our study to compare the increase of NBS (planted mangroves) throughout the years. The area of natural mangroves in 1962 is observed as 4660 ha (Fig. 6) and the area of the mangrove forest patches increase as time passes. The time series data shows a continuous increase in the mangrove forest patches and the net mangrove forest area in the years 1990 and 2021 is 49,933 ha and 53,977 ha, respectively. As we move forward from 1962 to 2021 (Fig. 5b–g), we observe a reduction in waterbodies and a sharp increase in homestead vegetation (settlement) and agricultural land. The settlement increased from 130,130 ha (1962) to 284,667 ha (2021) (Fig. 6) and the agricultural land increased from 515,719 ha (1962) to 540,888 ha (1980). However, as the settlement increases the agricultural land shrinks due to the demand for infrastructure development and settlement. Therefore, agricultural land decreased from 540,888 ha (1980) to 459,099 ha in (2021) (Fig. 6). Figure 5 also spatially illustrates the scenario of the spatio-temporal transformation of the land (Appendix Table 7). The LULC classification has been done with an acceptable level of accuracy (Appendix Table 8). The spatio-temporal distribution of the NBS and LULC guides the study to assess the neighborhood

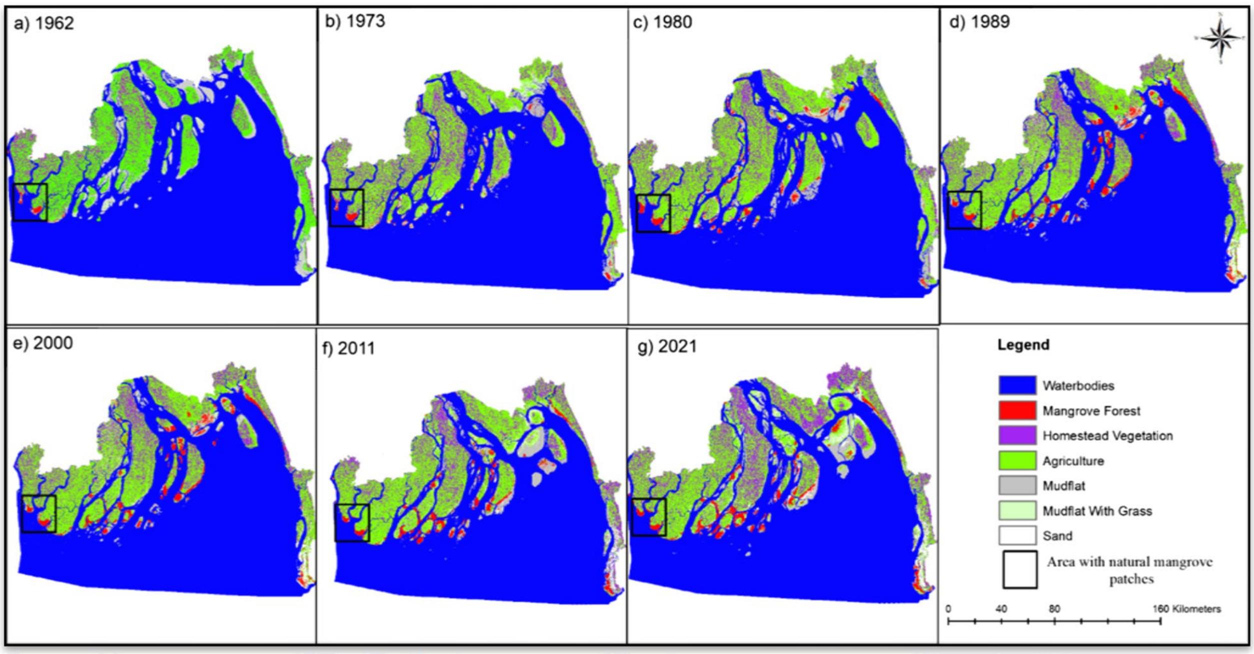


**Fig. 5** Land use and land cover data from 1962–2021. The red-colored mangrove forest represents GoB's NBS interventions except for the areas marked in the black box

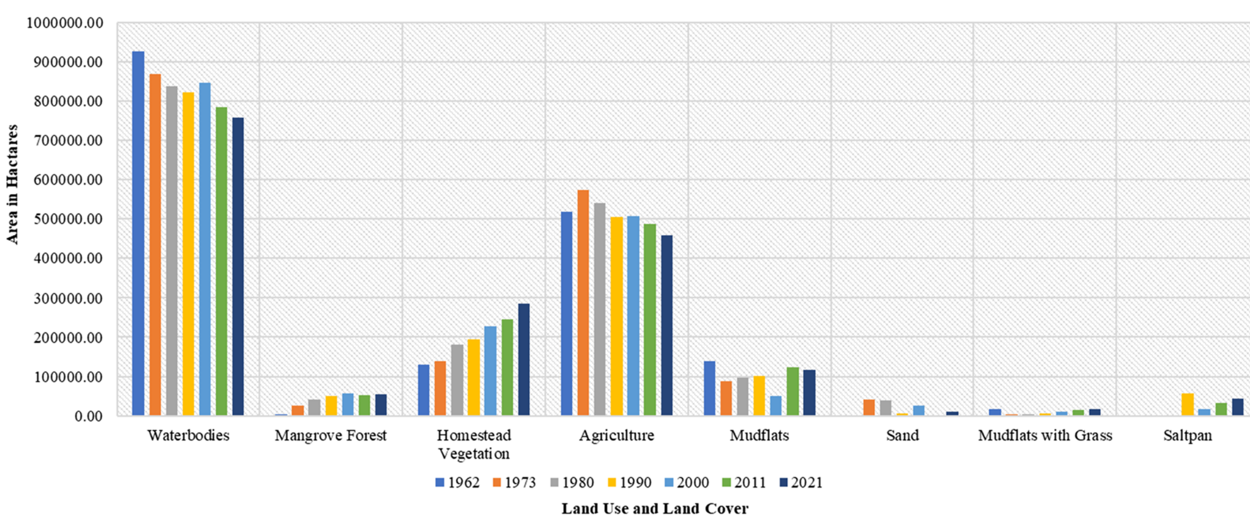


**Fig. 6** Land use and land cover statistics by year (1962–2021)

of each of the mangrove patches to have the understanding, of whether the development of mangrove patches helps increase or reduce some other land use and land cover categories. As we observe the data (Fig. 6), we can see a substantial number of waterbodies decreased as the planted mangroves increased and so went the agricultural lands and mudflats. This information gives us the broader idea that the increase in NBS can subsequently reduce the waterbodies, hence stabilizing the land areas.

**Table 4** Correlation matrix prepared for the whole study area of the coast

| | Waterbodies | Mangrove forest | Homestead vegetation | Agriculture | Mudflats | Sand | Mudflats with grass | Saltpan | Year |
|---|---|---|---|---|---|---|---|---|---|
| Waterbodies | 1 | | | | | | | | |
| Mangrove forest | − 0.844 | 1 | | | | | | | |
| Homestead vegetation | − 0.910 | 0.852 | 1 | | | | | | |
| Agriculture | 0.664 | − 0.538 | − 0.838 | 1 | | | | | |
| Mudflats | 0.018 | − 0.470 | − 0.093 | − 0.289 | 1 | | | | |
| Sand | 0.191 | − 0.027 | − 0.319 | 0.745 | − 0.635 | 1 | | | |
| Mudflats with grass | − 0.070 | − 0.127 | 0.352 | − 0.687 | 0.527 | − 0.721 | 1 | | |
| Saltpan | − 0.719 | 0.661 | 0.670 | − 0.716 | 0.085 | − 0.583 | 0.107 | 1 | |
| Year | − 0.931 | 0.864 | 0.989 | − 0.796 | − 0.107 | − 0.307 | 0.308 | 0.692 | 1 |

### Effectiveness of the NBS intervention

A correlation matrix has been conducted on the overall database of 7 years of land use and land cover data to observe the relationship between the land use and land cover (Appendix Table 9). However, as the study is concerned about the NBS, we especially emphasized on the relationship among the mangrove forest, waterbodies, mudflats, agriculture, and homestead vegetation (settlement) to understand the effectiveness of the NBS intervention. The correlation matrix (Table 4) presents a high negative correlation between the water bodies and the mangrove forest, which means if the mangrove forest increases the waterbodies decreases. The correlation is significant at 0.05 on a two-tailed test. However, as we observe the correlation between the mangrove forests and homestead vegetation, we can see a highly positive correlation (significant at 0.05), but there is a moderate negative correlation between a mangrove forest and the agricultural land. However, the correlation is found as statistically non-significant. The correlation is performed on the whole study area that assumes that the NBS (planted mangroves) has its influence on the whole area. However, this assumption is not true as the planted mangroves in terms of land stabilization should have its influence on areas that are in close proximity to the patches. Therefore, the study considered the grid-based assessment technique if an established mangrove patch has its influencing zone within 1 km of the mangrove patch. Based on this assumption, the study recorded the planted mangroves areas along with other land use and land cover area in each grid and conducted a correlation matrix on the sum of each land use and land cover category. In this exercise, the correlation matrix shows a strong positive correlation between planted mangroves and agricultural land (Table 5). The correlation is also found to be statistically significant at 0.05 (2-tailed). The correlation explains that, within 1 km of any mangrove patch, if the mangrove areas increase then the area of agricultural land increases.

It is observed that (Fig. 7a–f) as the time passes, the stabilization of lands occurred. The maps above show the exact situation of the land accretion and stabilization in every 1 km × 1 km grid. The above map shows two tests cased namely for Bhola and Hatiya-planted mangrove forest.

Moreover, to understand more of the nature of the relationship between the independent and dependent variables, the study used the panel data regression method

**Table 5** Correlation matrix prepared on the LULC data of 1 km × 1 km grid

| | Waterbodies | Mangrove forest | Homestead vegetation | Agriculture | Mudflats | Mudflats with grass | Sand | Year |
|---|---|---|---|---|---|---|---|---|
| Waterbodies | 1.00 | | | | | | | |
| Mangrove forest | − 0.84 | 1.00 | | | | | | |
| Homestead vegetation | − 0.55 | 0.43 | 1.00 | | | | | |
| Agriculture | − 0.89 | 0.81 | 0.66 | 1.00 | | | | |
| Mudflats | − 0.85 | 0.72 | 0.36 | 0.67 | 1.00 | | | |
| MFG | − 0.65 | 0.68 | 0.07 | 0.31 | 0.79 | 1.00 | | |
| Sand | − 0.71 | 0.70 | 0.60 | 0.53 | 0.44 | 0.61 | 1.00 | |
| Year | − 0.96 | 0.89 | 0.62 | 0.93 | 0.72 | 0.53 | 0.77 | 1.00 |

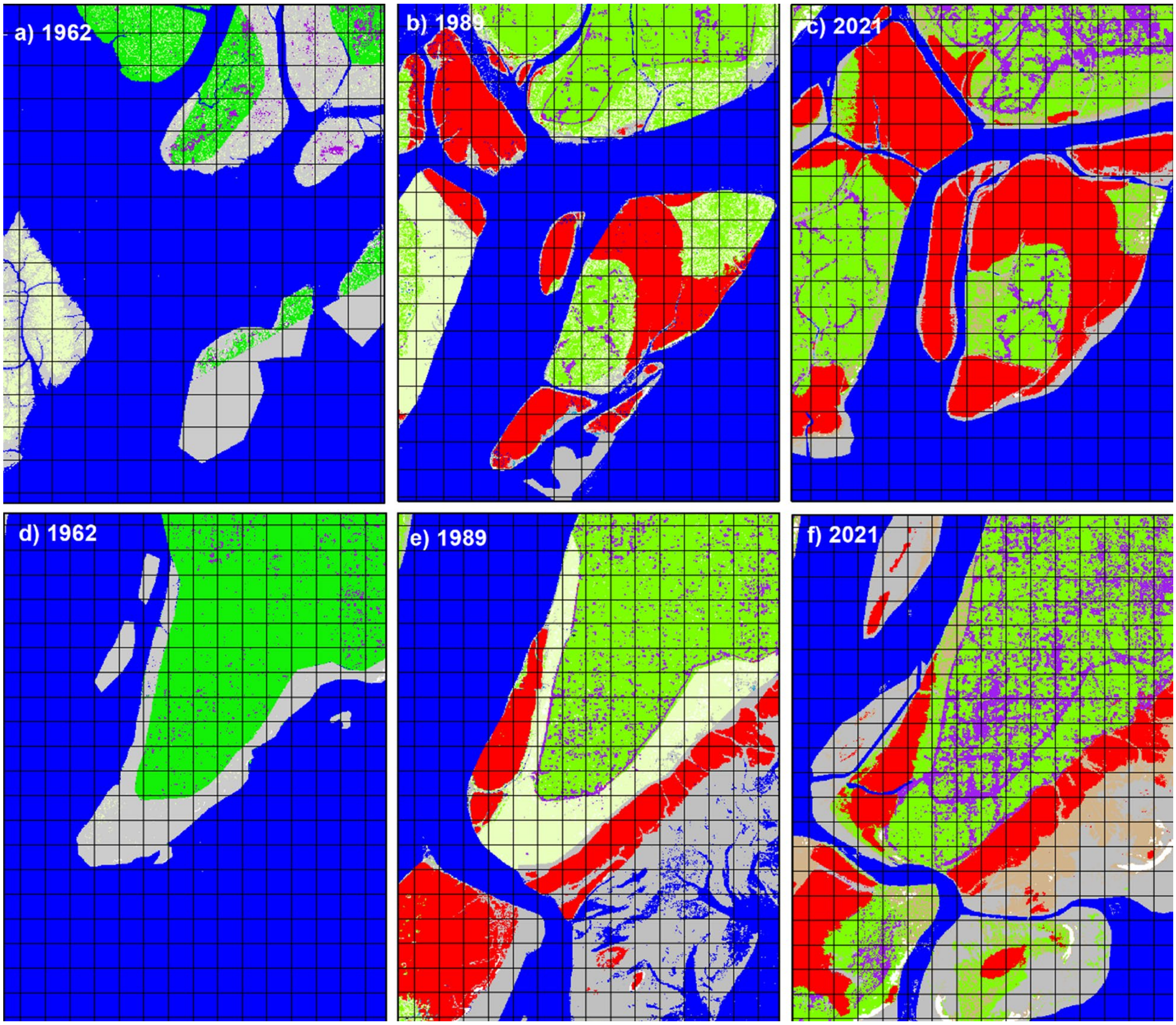


**Fig. 7** A close-up view of the relationship between the NBS (mangrove afforestation) and agriculture, mudflats, homestead vegetation, etc.

to avoid biases. Panel data regression models have been used to quantify the relationship among the features. The panel data regression model has been found effective and useful to have the concrete results for the relationship between a mangrove forest and agriculture. The panel data regression model shows that there is a strong correlation between waterbodies, mangrove forest, mudflats, year and agriculture. The regression summary shows that the correlation is 0.88 (Table 6) as multiple $R^2$ value and the adjusted $R^2$ value is observed to be 0.78. The $R^2$ value suggests that 78% of the observation can be explained with this model. Based on the ANOVA test, it is observed that the result is statistically significant. The dataset investigates 47,726 cases under 7 temporal years which suggests no biasness and thus the significance value is 0. Based on significance level, the study has rejected the null hypothesis and accepted that there is a significant relationship between our dependent variable agriculture and waterbodies, mudflats, Mangroves, and years. The relationship is also self-explanatory, as the increase of mangrove forests on the coast will decrease the waterbodies due to the presence of mangroves. Moreover, as the mangrove significantly increases the agriculture, the agriculture land would be one of the transformed forms of waterbodies. Again, for mudflats, mangrove forest grows on the mudflats and helps stabilize it through its roots. Therefore, there is a positive relationship is 0.72 between mangroves and mudflats. More importantly, mudflats transform into agricultural land, therefore, to become a new agricultural land, the mudflats need to

**Table 6** Summary output of panel data regression model

| **Summary output** | | | | | | |
|---|---|---|---|---|---|---|
| *Regression statistics* | | | | | | |
| Multiple *R* | 0.878 | | | | | |
| $R^2$ | 0.772 | | | | | |
| Adjusted $R^2$ | 0.772 | | | | | |
| Standard error | 13.518 | | | | | |
| Observations | 47,726 | | | | | |
| ANOVA | | | | | | |
| | *df* | *SS* | *MS* | *F* | *Significance F* | |
| Regression | 4 | 29,227,402.58 | 7,306,850.644 | 39,983.587 | 0 | |
| Residual | 47,721 | 8,720,833.664 | 182.7462472 | | | |
| Total | 47,725 | 37,948,236.24 | | | | |
| | *Coefficients* | *Standard error* | *t Stat* | *P-value* | *Lower 95%* | *Upper 95%* |
| Intercept | − 105.9657 | 6.4994 | − 16.3037 | <0.0001 | − 118.7048 | − 93.2267 |
| Waterbodies | − 0.6377 | 0.0016 | − 387.0041 | 0 | − 0.6410 | − 0.6345 |
| Mangrove | − 0.6877 | 0.0037 | − 182.5637 | 0 | − 0.6951 | − 0.6803 |
| Mudflats | − 0.6924 | 0.0031 | − 219.9640 | 0 | − 0.6986 | − 0.6863 |
| Year | 0.0851 | 0.0032 | 26.0935 | <0.0001 | 0.0787 | 0.0915 |

be transformed to agriculture land. We can also observe a good positive correlation (0.67) between mudflats and agricultural land. Finally, we observe a positive correlation between time and the increase in agriculture. This is because the mangrove forest has a cumulative effect as the patch gets increased by the regeneration of mangrove species, thus enhancing the stabilization process. Therefore, based on the statistical analysis, we can draw a conclusion that there is a moderately high relationship of increasing agricultural land due to planted mangroves.

### Quantification of the socio-economic benefits of NBS

Based on the developed methods of quantifying the socio-economic benefits of the mangrove afforestation-related NBS, the study assessed the economic value of the agricultural (settled) land. The study quantified the stabilized lands due to NBS for 6 years starting from 1962 to 2021. Since 1962 is our baseline, and there were no NBS interventions before 1965, the year 1962 was excluded from the NBS-derived ecosystem service/ economic valuation.

### Estimation of the stabilized land

The classified land use and land cover map shows the presence of mudflats in the study area. The trend of LULC data represents the dynamic characteristics of the mudflats as the class goes through severe erosion and accretion activities. The area of mudflats was 140,009 ha in 1962 and in 2021 the class falls to 116,143 ha. The data represent severe instability as the class does not have any specific trend. This uncertainty of the class proves that the mudflats go severe erosion and accretion activities. Therefore, in this study siltation and formation of mudflats have not been considered as the stable land class. In this study, we considered agricultural land as stable land, because for agriculture the land must be settled as the agricultural activity is the investment. No farmers and smallholders will not invest in the unsettled land that may become eroded at any point of time. Therefore, as we identified the agricultural land using the satellite image interpretation, we considered the agriculture (AC) class as the stable land. With the applied methodology to quantify the stable land the study came out with the stable land database and prepared visual interpretation through maps and graphs. The result shows that in 1962 the area of stable land in 1962 is 0, this is because 1962 is the baseline year and there were no previous years to compare. As we progressed through the time, we observe an increasing trend from 47,632 ha (1973) to 102,227 ha (2021) except the year 1990, when the area of stable land dropped down to 55,086 ha (Fig. 8). However, the event is also well explanatory, as we observe huge erosion activities in the coast and the Meghna estuary. Moreover, after 1990, during 2000–2021, in 20 years' time span, we see

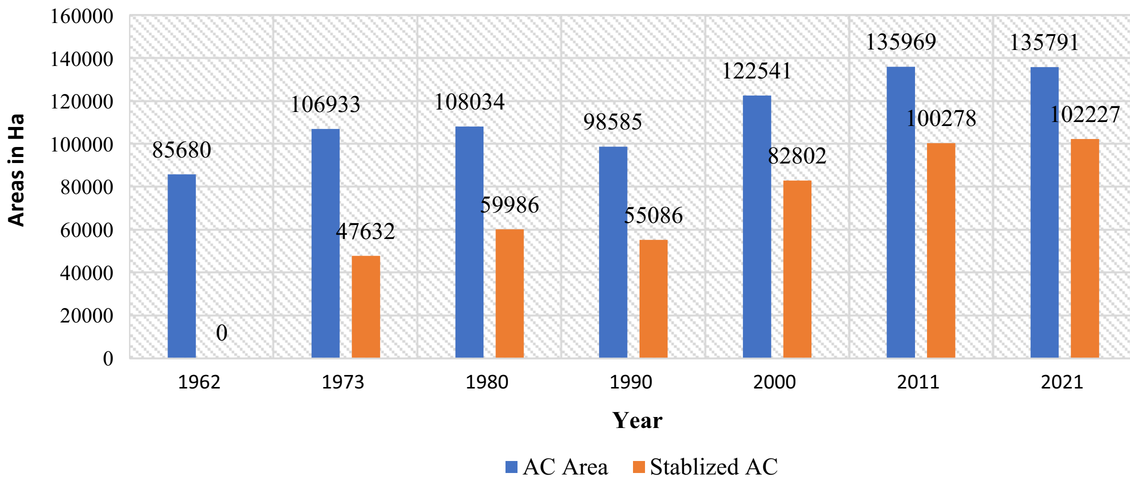


**Fig. 8** Agricultural land (AC) vs net stable land by year (1962–2021)

very slow growth of stable land and even in 2021 the area of stable land drops a little bit. The reason behind the decline is rapid growth of population and demands of settlement. The stable land was therefore transformed into settlements or in other term homestead vegetation class. The events are also aligned with the trend of total agricultural land (AC).

As observed from the spatial distribution of the stabilized land in Fig. 9a–f, we can see that the rate of stability is much higher in the Patuakhali Coastal Afforestation Division (CAD) which is in the southwestern part of the study area (Fig. 9a, b). The central coast (Bhola CAD and part of Noakhali CAD) also have notable stability of land although has its dominance in the western part (Fig. 9a, b). As for the eastern coast (Chittagong CAD), we see very slow and nominal growth of stable lands (Fig. 9a, b). However, moving forward in time (1990–2000), we can see an influential amount of stable land on the central coast and this time the dominance is observed in the Noakhali CAD. However, Patuakhali CAD is still cruising in terms of stabilizing the land (Fig. 9c, d). Again, the progression in stabilizing the land, the Chittagong CAD is still far below in terms of the rest of the CADs (Fig. 9c, d). During 2000–2021 in 20 years, we observe great contributions in both Noakhali CAD and Chittagong CAD in terms of stabilizing the lands (Fig. 9e, f). During the 60 years cycle, Patuakhali CAD shows a positive pattern in stabilizing the lands. This is the period (2000–2021) when the study observed an influential number of areas stabilized in the southeastern corner of the study area. However, the red tone of the area again indicates, although there is a signature of stabilization, the rate of stabilization is not as satisfactory as the Patuakhali and Noakhali CAD or in other words central coast region (Fig. 9e, f).

### Economic valuation of NBS-derived socio-ecological benefits

Agricultural land provides multiple benefits to the people and the community such as social security, food security, livelihoods, economic value, etc., in terms of temporal change in the total land price, in general, the land price follows the trend of stable land area. However, it is to be noted that the land price was calculated based on the cadastral boundary rate for each of the local land record office from 2018 to 2020. Figure 10 shows a sharp cruising trend from 1973 to 2011 and then falls down a little bit. In terms of 1990–2011, in 21 years the land value rose so high following the increasing trend of stable land. The drop in price from 2011 to 2021 might be the reason for the encroachment of the agricultural land with the settlement. Although land prices increased overall, we, however, see variations of growth, especially in 1990. There could be multiple reasons for the variation, e.g., erosion and spatial variation of the land price.

The spatial distribution of the land price across the study area for 6 different years is capable of describing the land price scenario with a combination of the total land price of the study area. Figure 11a presents the land price status for the year 1973. The land price status shows that although there have been a substantial number of areas that became stabilized in Patuakhali CAD,

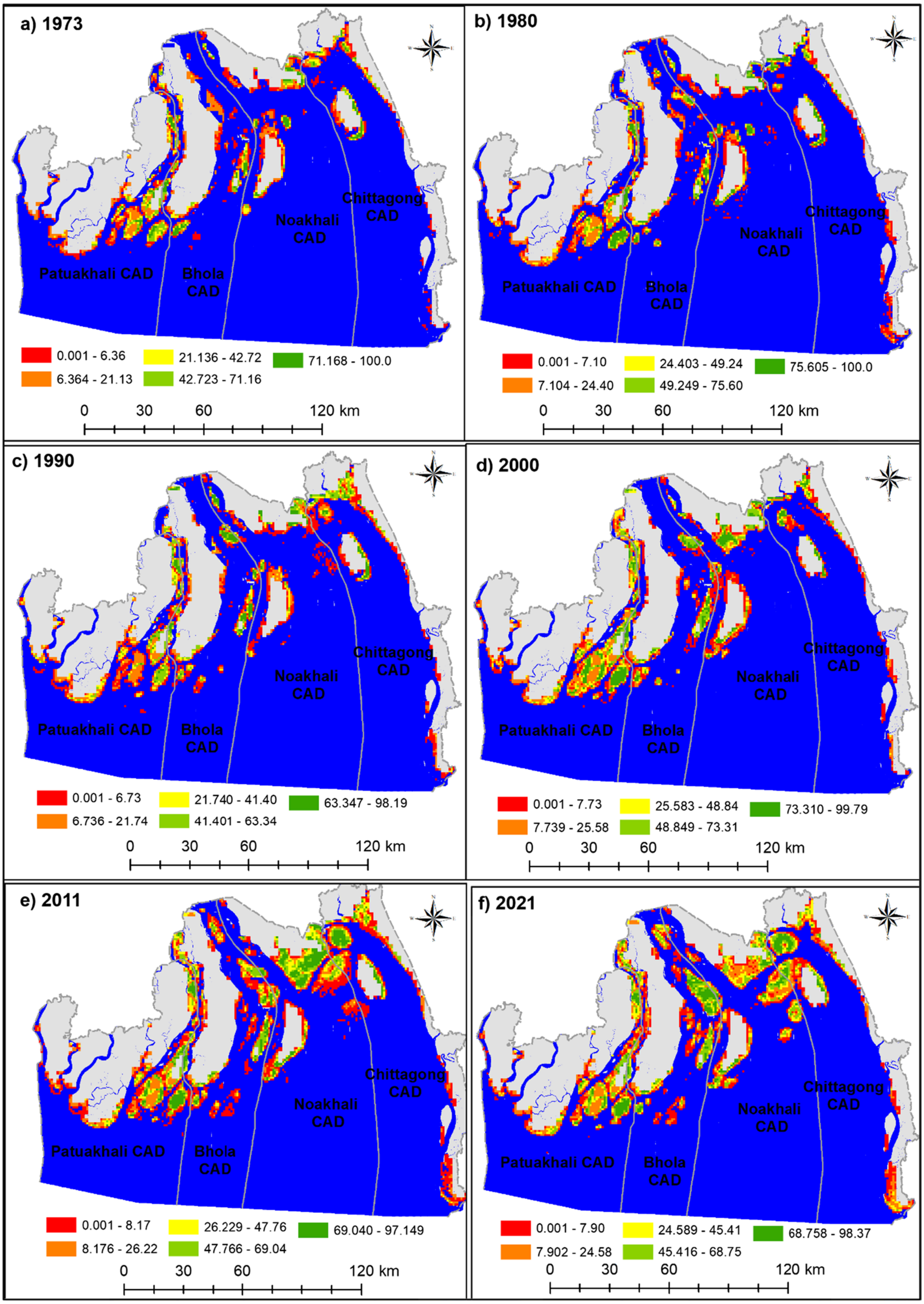


**Fig. 9** Spatial distribution of the stabilized land in ha (1962–2021). The color scheme denotes the amount of stable land portion within 1 km × 1 km grids

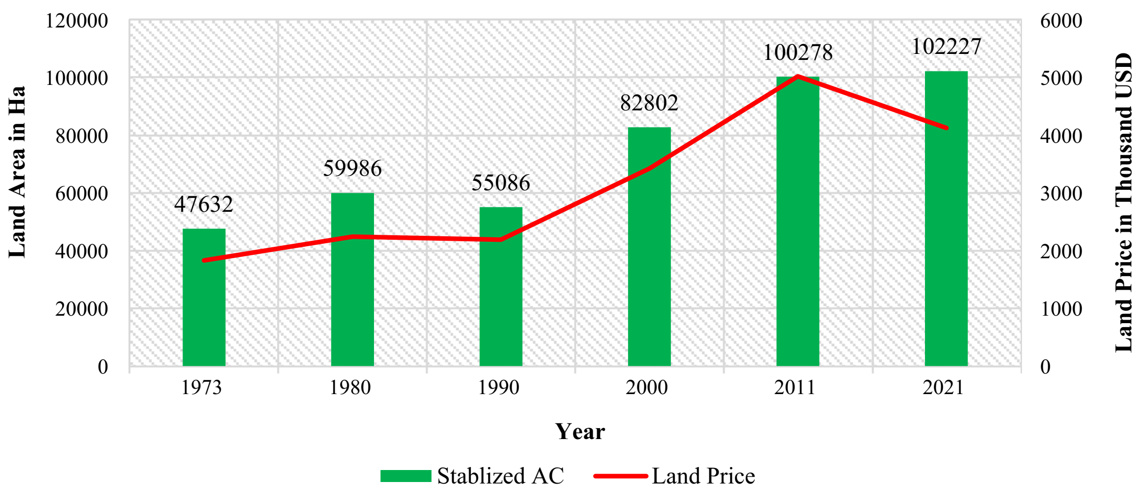


**Fig. 10** Land price of the stable lands as part of economic valuation of NBS effectiveness

the color of the grids is yellow at maximum in Fig. 11a. This means, the land price is lower, or the agricultural lands are yet to achieve compactness. At the same time, if we observe the land price in Noakhali CAD, the upper region of the Noakhali CAD exhibits a high price area. This scenario indicates the land price is way too high in that region which also compliments our land price distribution map of the study area (Fig. 3). The spatial distribution map in Fig. 11c shows low price grids (570–1999 USD/100 ha) in Patuakhali grids which used to be 1339–3221 USD/100 ha in 1973 (Fig. 11a). This explains the erosion of land and agricultural lands being a discrete feature.

If we closely observe the mangrove area map presented in Fig. 12, we can see that in that region (marked in a pink circle) there is no mangrove in 1990, which again explains how the presence of planted mangroves can contribute to land stabilizing thus to increase the land price of agricultural lands. As we move forward from the year 2000 to the year 2021, we observe that the land price increased especially in the Noakhali CAD which complements and follows all the vital elements of land price, i.e., the presence of mangroves, stabilized land, and the unit price of land. The results, therefore, show how the NBS can protect the land from erosion and stabilize land to transform into agricultural land, and more importantly, how the stable lands provide social and economic benefits to the community.

### Estimation of the ecological benefits derived from NBS

In 1962, the stock of the total carbon in mangrove forests was 599.57 kt (Fig. 13). However, as the mangrove forest is a natural forest and existed before 1965, the sequestrated carbon is not considered NBS-derived carbon and is addressed separately (Fig. 14). However, from 1973 to onward, we see a steep climb of carbon stock in the study area observed from 2072.95 kt (1973) to 5879.86 kt (2021). As we observe through the spatial distribution of the carbon stock, we see that in 1973 the stock value in carbon grids is low to moderate range and as we move forward with time, the stock value per grid increases (red color) (Fig. 15). This explains the cumulative increase in mangrove area due to the introduction, maintenance, and management of the NBS. In the year 2000, the stock of carbon is the highest at 6168.5 kt, but the carbon stock did not increase due to the encroachment of the mangrove forest by land transformation and in our case transformation from mangrove to agriculture and settlement.

## Discussion

IPCC (2014) termed low lying coastal zone of Bangladesh as a “Key Societal Hotspot” to climate change that constitutes 20% of the country’s area and 28% of the population of Bangladesh (BBS 2011). The observed and projected vulnerability of Bangladesh to climate change include sea level rise (IPCC 2014), increasing salinity trends (Islam et al. 2015), increasing frequency and intensity of tropical cyclones and storm surges (Hoque et al. 2019), deteriorating coastal ecosystem (DoE 2015), shoreline erosion

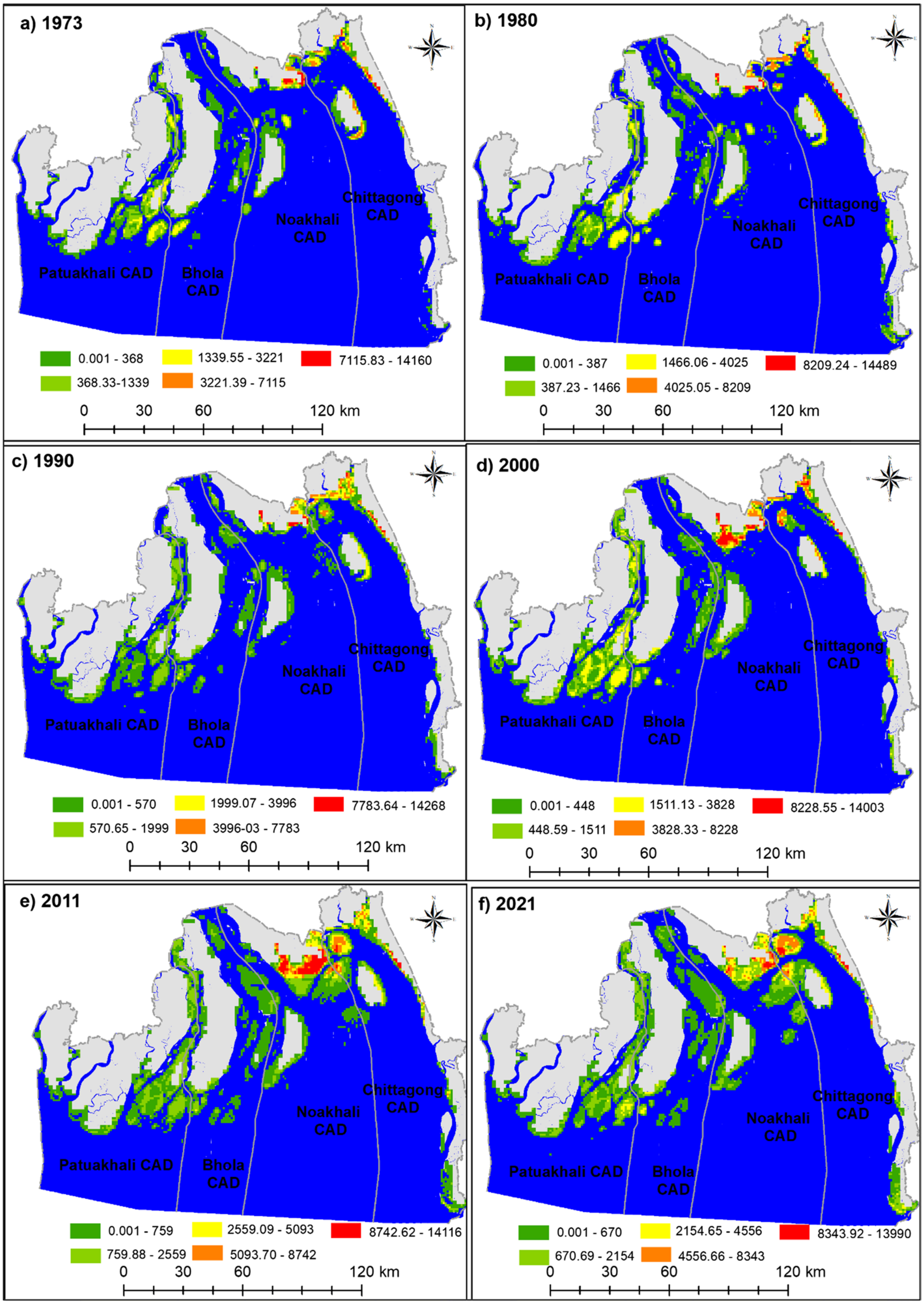


**Fig. 11** Spatial distribution of land price (in USD) of the stable land (agricultural land)

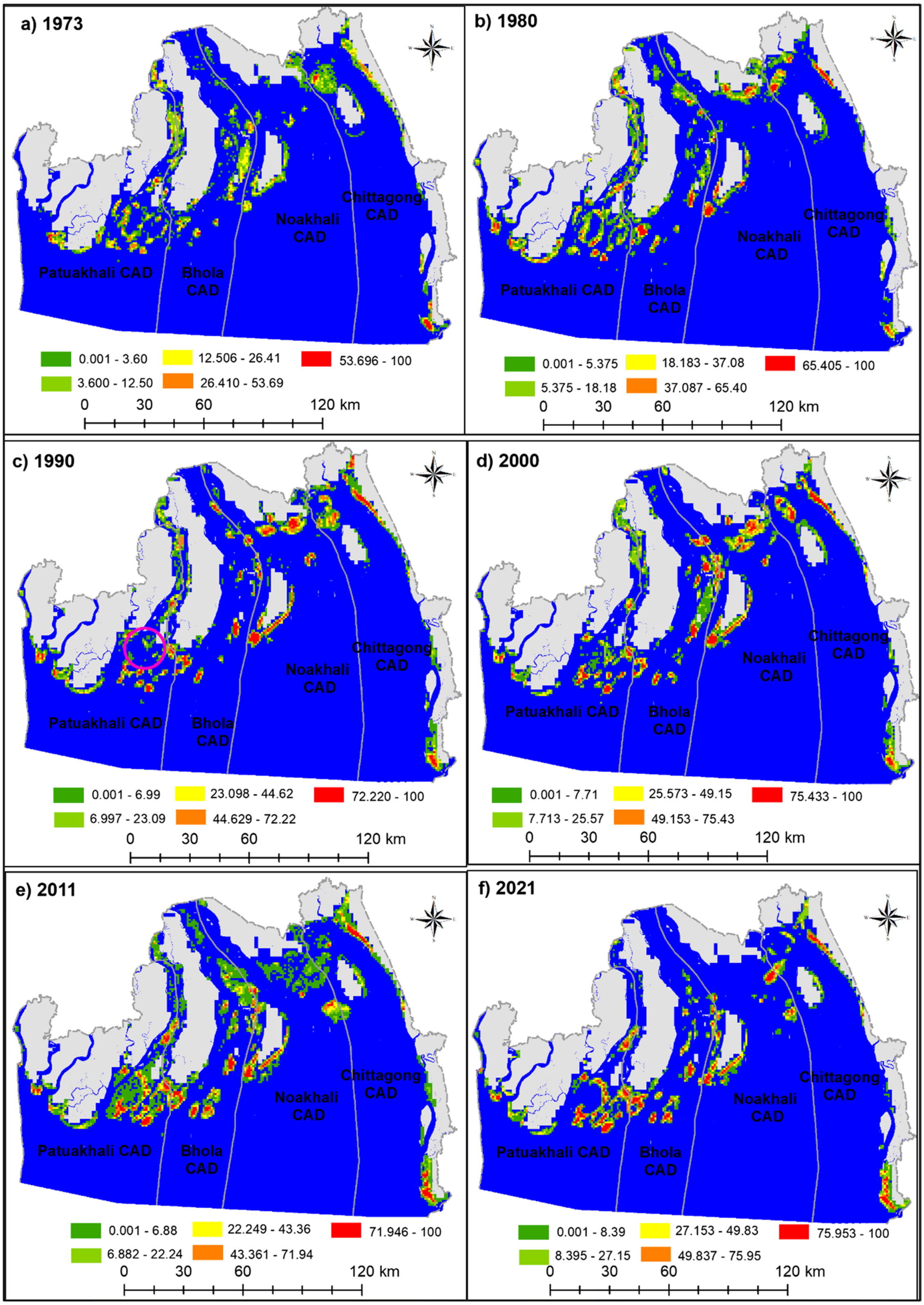


**Fig. 12** Distribution of the mangrove across the study area (in hectares) in 1 km × 1 km grid based on their proportionate share of area (1973–2021)

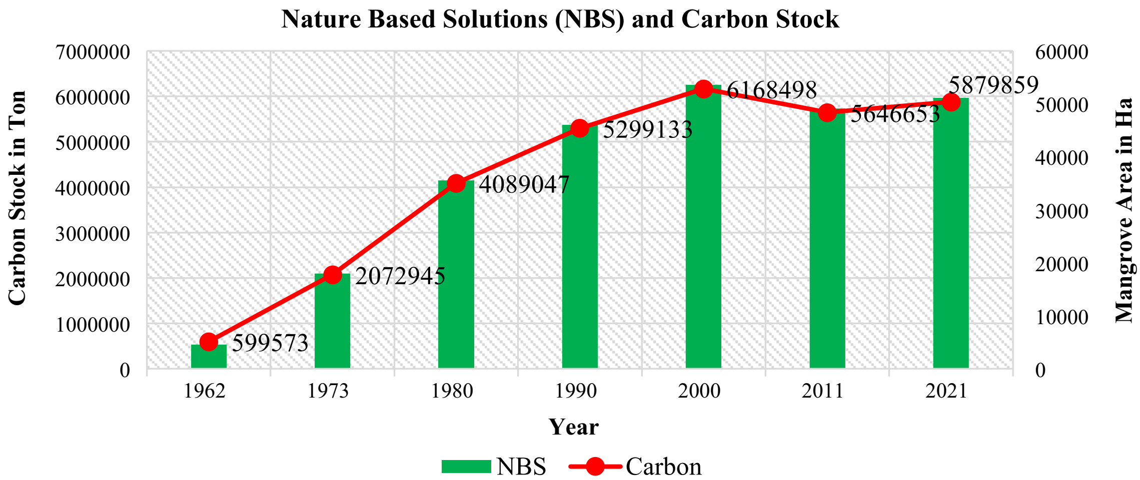


**Fig. 13** Temporal carbon stock in the coast of Bangladesh due to the intervention of NBS by 60 years of afforestation and reforestation programs

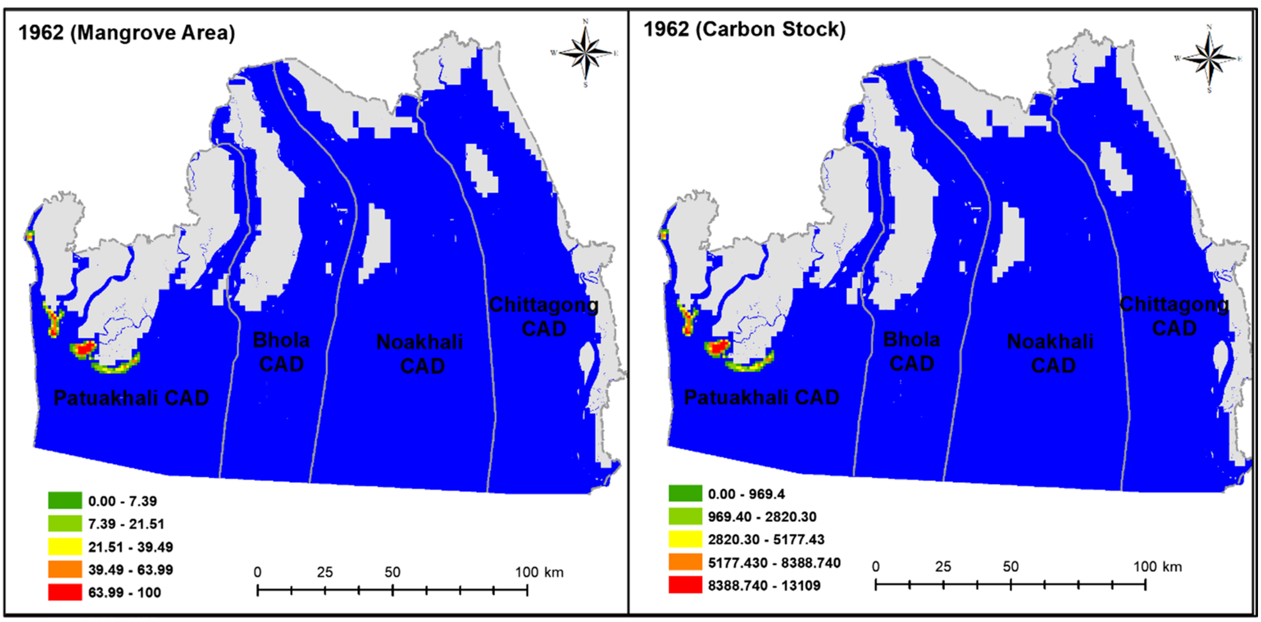


**Fig. 14** Mangrove area and carbon stock in 1962

(Mahmood et al 2020; Roy and Mahmood 2016) and sedimentation (Islam et al. 2015) which have become a serious threat to the lives, livelihoods and sustainable development of the country (Mahmood and Mahbub 2018).

Since Bangladesh is highly vulnerable to the adverse impacts of climate change, coastal mangrove afforestation as a part of biodiversity conservation and the NBS option is likely to keep it more adaptable to the anticipated adverse impact of climate change (Martin et al. 2020) which has long been practicing by Forest Department. During 1965–2013, the Forest Department planted 209,138.50 ha of coastal area with more than 92% mangrove species (BFD and UNDP 2018). Selection of monoculture species such as *S. apetala* encounters several

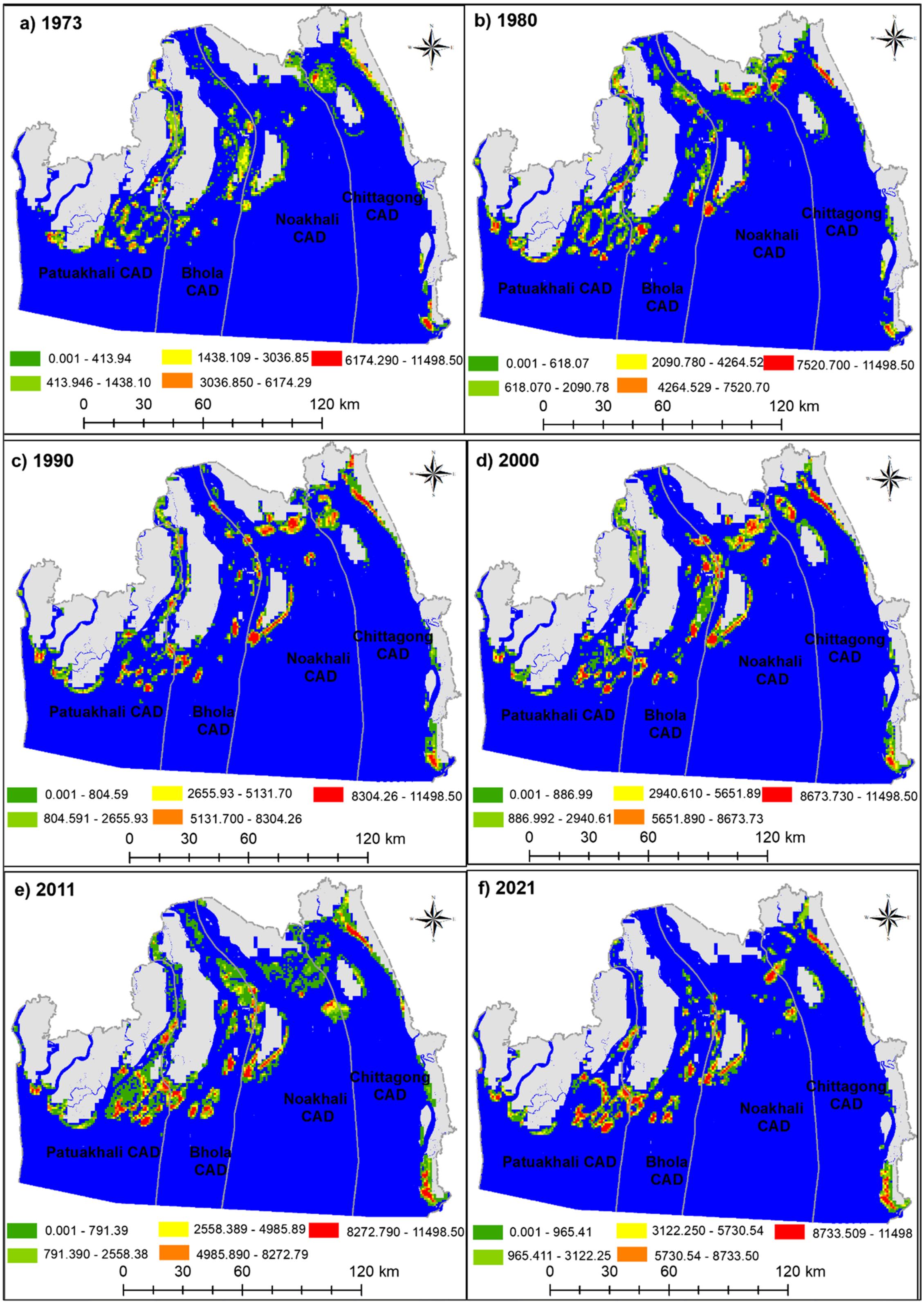


**Fig. 15** Spatio-temporal representation of carbon stock in the coast of Bangladesh from 1962 to 2021

problems due to geographical changes in the forest floor, plant succession, seedling mortality lack of inundation due to rapid sedimentation (Islam et al. 2013). Also, a lack of community-based participatory approach, illegal grazing, illicit tree felling, and forest land encroachment led by powerholders tend to serious damage to plantations (Al Mamun et al. 2021). All these reasons caused a loss of up to 80% of planted monoculture mangrove trees (Islam and Rahman 2015). Since 2013, the Forest Department has implemented a US$ 35 million project administered by the World Bank and funded by the Bangladesh Climate Change Resilient Fund which included multiple species instead of monoculture with the emphasis on various indigenous species of seedlings in all the new plantation sites which will help the restoration of biodiversity and its enhancement in the country (DoE 2015). Initiatives like "Community-Based Adaptation to Climate Change through Coastal Afforestation Project (CBACC-CF)" (2008–2016) of the United Nations Development Program (UNDP), supported by the least developed countries (LDC) Fund and "Climate Resilient Participatory Afforestation and Reforestation Project (CRPARP)" (2013—2016) of the Forest Department, funded by Bangladesh Climate Change Resilience Fund (BCCRF), have redefined coastal afforestation as a NBS option and initiated different types of plantation techniques through incorporating long-term spatial and temporal risks of climate changes for enhancing sustainability and protective capacity of coastal forests (DoE 2015). Under CBACC-CF Project a total of 6372 ha of coastal afforestation were done (Ahammad et al. 2013). In the period of 2013–2016, a total of 7485 ha of mangroves and *Casuarina* were planted along the coast under CRPARP Project ( IUCN 2016). At the onset of 2018, a total of 390,688 ha of coastal afforestation has been conducted in 498,150 ha of the coastal area (about 73% of the total area) (BFD and UNDP 2018) which was handed over to the Forest Department under the Ministry of Environment, Forest and Climate Change (MoEFCC) for coastal afforestation and declared as reserved forests. Besides, many big and small climate change adaptation projects such as Mangrove for Future (MFF), Climate Resilient Ecosystems and Livelihoods (CREL), Sundarbans Environment and Livelihood Security (SEALS) also practiced coastal mangrove afforestation using community-based approaches in biodiversity-rich ecosystems, sometimes in connection to resilience building and markets development (DoE 2015) which is expected to be further promoted by "Sustainable Forests and Livelihoods" (SUFAL 2018–2023) project. The SUFAL is a USD 175 million World Bank-funded program of the Forest Department of Bangladesh that has introduced "collaborative forest management" to engage people in the forest and non-forest area management.

Previous studies (Islam and Rahman 2015; Al Mamun et al. 2021; Menéndez et al. 2020) focus on benefit transfer or economic valuation instead of process-based methods that can account for local variation in characteristics of storms, sources of flooding in the ocean, mangrove habitat, coastal topography and bathymetry, inland receptors of damage. However, there are several quantitative works done for the Bangladesh coast focusing on vulnerability, adaptive capacity, and resilience assessment where many of the work attributed the presence of mangroves as an asset for the protection and resilience of the community (Mahmood et al. 2020; Hasan et al. 2020). Also, there have been works done to show the protection value of mangroves against the natural disaster and these studies considered SRF for their case study (Mahmood et al. 2021; Hasan et al. 2020; Sarker et al. 2016; Payo et al. 2016). However, no study has been conducted to assess the effectiveness and influence of the mangrove forest plantation that have been raised as part of NBS. The effectiveness of afforestation and reforestation of mangroves as NBS option varies significantly across regions and countries due to differences in natural hazard characteristics, socio-economic context, mangroves extent (Menendez et al. 2020). It has been seen in this study that mangrove afforestation and reforestation programs benefits depend on the degree of exposure, i.e., what (inland topography behind these mangroves) and who (population dynamics) is at risk to climate change, effectiveness tend to be higher on low lying densely populated flatter floodplains where storm surges travel far, relative to steeper floodplains; therefore Bangladesh received greatest co-benefits from mangroves in terms of people protected due to the high density of coastal populations which is consistent with the findings of Menendez et al. (2020).

Therefore, the similarity and commonality of this study with other work (Mahmood et al. 2020; Menendez et al. 2020; Martin et al. 2020), there has been very limited secondary sources available to compare the findings with. As assumed and designing of the study, the CORONA (1962–1965) and Landsat (1972 and onwards) satellite evidence-based information has been crucial in comparison of the NBS effectiveness since the mangrove afforestation and reforestation program was introduced in 1965 in the Bangladesh coast (DoE 2015). As progressed through time, there has been an increasing trend of NBS-derived (mangrove afforestation) stable land area (agriculture) till 2000, followed by the stagnant growth between 2000 and 2021. The study, therefore, explored the case and found that the coastal mangrove forest area has gone through a huge transformation which is consistent with the findings of Al Mamun et al. (2021) and Hasan et al. (2020). The total transformed

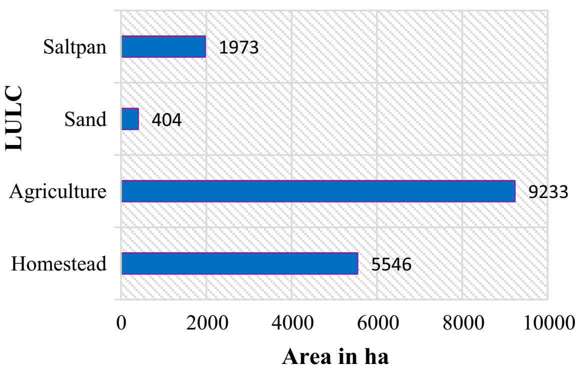


**Fig. 16** Transformation of mangrove forest into other LULC classes for the period of 2000–2021

land is 17,157 ha through four LULC classes. among these, the homestead is responsible for 5546 ha of land transformation (Fig. 16). If the mangrove forest had not transformed, the net stable land would have been higher. The major transformation has happened in the Noakhali CAD (Fig. 17) because of the higher land price which indicates land transformation through encroachment.

From the field survey of this study, major challenges identified in coastal mangrove afforestation projects as a part of the nature-based solution include various factors such as hazard conditions (Mahmood et al. 2020; Menendez et al. 2020) (e.g., coastal erosion, coastal inundation, cyclone and related storm surge, changes in salinity, sea level rise, etc.), geographical context (e.g., changing estuary channel, sedimentation, downstream flow, etc.), plantation management (DoE 2015) (e.g., site suitability, species selection, after-care, etc.), anthropogenic activities (Menendez et al. 2020) (e.g., people' cutting mangrove trees/saplings for firewood, encroachment, development activities like an industrial park, sea-port, etc.). Additionally, climate change has been significantly affecting the temporal and spatial distribution of ecosystem processes and functions, thus modifying the delivery of associated services (Raymond et al. 2017) leading to considerable variation across geographical areas and sectors (Calliari et al. 2019). In most of the cases, coastal afforestation (mangrove afforestation) projects are more focused on quantity rather than quality. The use of monocultures with non-native species produces maladaptation to climate change in the long term and negatively impacts biodiversity and sustainable development (Menendez et al. 2020). Also, the loss of mangroves in coastal afforested sites has happened due to the conversion for aquaculture or agriculture and coastal development which contributes to increasing coastal risk (Spalding et al. 2014). Given the coastal vulnerability of Bangladesh, plantation survivability is a big concern (Islam and Rahman 2015). The Forestry Sector Master Plan (FSMP) (2017–2036) noted that due to the failure and destruction from natural calamities, the survival rate of coastal afforestation is low, the actual area under coastal plantation now stood 61,574 ha against total 209,138.50 ha (planted till 2014) (DoE 2015; Islam and Rahman 2015). CRPARP (2013–2016) Project reported that some plantation parcels of which the measured area and survival percentage

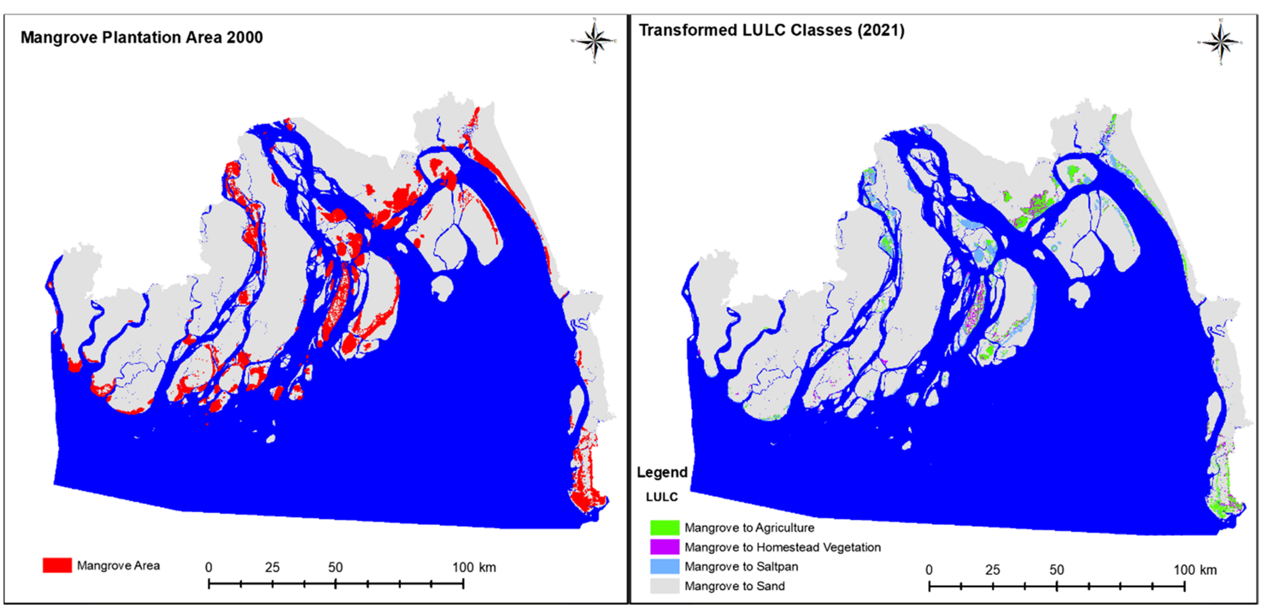


**Fig. 17** Transformation of mangrove forest into other LULC categories (2000–2021)

are deviant due to some natural and anthropogenic events, e.g., cyclones, erosion, etc. (IUCN 2016).

Bangladesh has long been trying to protect existing forests through protected area management by restoring the degraded forest areas and by expanding the forest in new coastal areas, sometimes involving people in all cases (DoE 2015) as an adaptation as well as NBS option to protect people and dynamic coast from the impact of climate change. Since the ongoing environmental and climate change may undermine ecosystem integrity, a more comprehensive evidence base is needed on the effectiveness of NBS (EC 2015). Most of the existing NBS frameworks are descriptive and difficult to translate from theory to practice because of lack of quantitative properties and to incorporate into mitigation plans (EC 2015; Eggermont et al. 2015; Cohen-Shacham et al. 2016). Also, none of the frameworks is able to quantitatively assess the effectiveness of NBS for disaster risk reduction (Raymond et al. 2017) and possible disservice (Martín et al. 2020) under the potential impact of climate change scenario (Pecl et al. 2017). In congruence with the finding of the paper, this study has been a pioneering attempt to statistically prove that if the NBS becomes effective it can bring multifold benefits (e.g., social, ecological, and economic) which can be quantifiable and complements the Climate Change Resilience of Place (C-CROP) model (Mahmood et al. 2022).

However, the study is not free from limitations, for example, mangrove forest grows over time and so increases the biomass and carbon. Therefore, it was required to study mangroves of different age groups. The study just used the average carbon value per ha of planted mangroves. Also, the present price of land is considered to estimate the land price for 1962 also which is another limitation, since the land price varies over time. The study used the freely available Landsat satellite images, but the use of high-resolution satellite images could incorporate many other factors and functions of the ecosystem. However, the lack of cloud-free data is one of the many constraints to address the issue. On the other hand, systematic and random errors of the Landsat sensor itself could have affected the delineation of coastlines. Another potential error source could be the presence of mixed pixels in Landsat data along edges which was addressed by several field visits to identify exact shorelines. During the field survey of this study, authors faced difficulties as some parts of the study area are remotely situated and less accessible. Although due to restricted field observation and other budgetary limitation, the study went through limited capacity depending mostly on the secondary sources of data of different quality, some of these are old while some have a coarse resolution. However, these limitations can be overcome by using high-resolution satellite data.

## Conclusion

Nature-based solution (NBS) is proposed to increase the transformative capacity of the socio-ecological system in the climate change context (Mahmood et al. 2022). Therefore, the main innovation of this study is to spatially establish the effectiveness of the NBS to enhance the resilience of the coastal community. However, there are two approaches to the mangrove afforestation as NBS option. If mangrove increases, the adjacent lands become stable where agriculture can occur. This seems a very good option considering the high density of the population and high demand for arable lands in Bangladesh. On the other side, if people cut down the mangrove patches and transform them for agriculture then it will diminish the ecosystem services from mangroves. Therefore, the government must protect the planted mangroves to avail the maximum ecosystem services from it. This study also shows the prospect of getting more agricultural lands through planted mangroves. Thus, it has filled up the severe lack of practical and targeted guidance for the processes that enable the assessment of the effectiveness of a particular NBS option through the consideration and assessment of co-benefits to the ecosystem within and across the stages of implementation and decision-making (Ürge-Vorsatz et al. 2014) and established that the planted mangrove forest can significantly contribute to stabilizing the newly accreted lands and eventually transform these lands into land use (e.g., agriculture). Although mangrove provides many direct and indirect benefits as part of the ecosystem (Martín et al. 2020), in this study we estimated the indirect benefits of the mangrove to the global natural system. Although climate change is a global phenomenon, the amount of carbon stored by the NBS-derived planted mangroves, surely can contribute to the deceleration process of climate change (Hasan et al. 2021; Mahmood et al. 2022, 2020). This work has been expanded to look at NBS relating to protected areas under the Panorama initiative, which aims to collect and share case studies of these solutions (Cohen-Shacham et al. 2016). Also, this study can be used for future work such as cost benefit analysis of other structural and nonstructural solutions compared to the NBS (mangrove afforestation) for the carbon reduction projects in the climate change context.

The concept of NBS is new and still in the development stage. The work of this study can be upscaled universally, especially for similar types of NBS intervention with more or better information, tools, and study resources. Also, based on the future LULC, there is good scope to predict the stable area for the next 60 years using the current regression model. There's a scope of incorporating Normalized Difference Vegetation Index (NDVI) and other vegetation indices to correlate the spectral signature of mangrove forests and the biomass of any grid to model the biomass and carbon status through a linear regression model.

Despite all the limitations, the generated results are still able to contribute to adaptation policy formulation in the context of climate change. Also, the study used overall correlation and 1 km grid-based correlation where 1 km grid-based correlation was found suitable for establishing the relationship between Mangrove and agricultural land. However, the best of the approach would have been to use a grid that is prepared based on mangrove influencing distance. This means, how far a mangrove patch can influence through protecting erosion and enhancing accretion. However, there was no study that documented this influencing relationship. Identifying the influencing distance of mangrove patches could be great research work for the scientific community to measure the effectiveness of the afforestation and reforestation based NBS. A Spatial Decision Support System (SDSS) can be developed to store and document the periodic monitoring assessment results and the new cutting-edge technology of Artificial Intelligence can be used to help facilitate future assessment, which will pave the opportunity to achieve better and faster climate change resilience and adaptation strategies with evidence-based mapping and monitoring.

## Appendix

See Tables 7, 8, and 9.

**Table 7** Land use and land cover statistics of the Bangladesh coast except Sundarban Reserve Forest (ha)

| LULC | Year | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1962 | 1973 | 1980 | 1990 | 2000 | 2011 | 2021 |
| Waterbodies | 1,902,690.00 | 1,844,700.00 | 1,814,830.00 | 1,797,727.50 | 1,822,270.00 | 1,759,650.00 | 1,733,130.00 |
| Mangrove forest | 4660.11 | 25,336.40 | 40,569.70 | 49,933.71 | 57,163.80 | 52,651.10 | 53,977.20 |
| Homestead vegetation | 130,130.00 | 139,252.00 | 180,055.00 | 194,773.16 | 227,236.70 | 245,775.94 | 284,667.90 |
| Agriculture | 517,719.00 | 574,056.00 | 540,888.00 | 505,778.59 | 507,937.00 | 486,192.50 | 459,099.00 |
| Mudflats | 140,009.00 | 88,377.10 | 96,747.00 | 100,523.85 | 49,233.70 | 124,464.00 | 116,143.00 |
| Sand | 2411.37 | 41,027.00 | 39,476.10 | 6664.80 | 26,232.60 | 2636.42 | 10,018.50 |
| Mudflats with grass | 17,826.00 | 4351.68 | 4084.42 | 5208.34 | 10,936.60 | 14,227.60 | 16,439.70 |
| Saltpan | 200.92 | 508.22 | 958.18 | 56,998.44 | 16,598.00 | 32,010.84 | 44,133.10 |
| Total | 2,717,608.40 | 2,717,608.40 | 2,717,608.40 | 2,717,608.40 | 2,717,608.40 | 2,717,608.40 | 2,717,608.40 |

**Table 8** Accuracy assessment for the land use and land cover classification for 7 classification years for the Bangladesh coast

| Class name | Producer's accuracy (%) | | | | | | | User's Accuracy (%) | | | | | | | Overall accuracy | Kappa coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1962 | 1973 | 1980 | 1990 | 2000 | 2011 | 2021 | 1962 | 1973 | 1980 | 1990 | 2000 | 2011 | 2021 | | |
| Waterbodies | 92.4 | 93.5 | 90.9 | 96.4 | 97.0 | 96.2 | 97.9 | 94.4 | 95.2 | 94.6 | 97.1 | 98.0 | 98.0 | 97.9 | 1962: 86.16% | 0.84 |
| Mangroves | 83.3 | 90.9 | 90.3 | 94.4 | 98.3 | 97.2 | 97.2 | 78.1 | 81.6 | 86.7 | 90.4 | 92.2 | 94.5 | 97.2 | 1973: 88.5% | 0.86 |
| Homestead vegetation | 92.1 | 91.5 | 87.7 | 91.5 | 94.2 | 95.6 | 94.8 | 88.6 | 95.6 | 92.6 | 92.9 | 97.0 | 95.6 | 94.8 | 1980: 86.35% | 0.84 |
| Agriculture | 83.3 | 87.2 | 87.0 | 90.9 | 95.3 | 93.4 | 92.5 | 83.3 | 87.2 | 82.5 | 87.0 | 94.6 | 89.2 | 90.0 | 1990: 91.14% | 0.90 |
| Mudflats | 88.7 | 88.2 | 84.7 | 85.9 | 95.2 | 90.9 | 100.0 | 94.8 | 96.8 | 94.3 | 98.2 | 98.4 | 98.4 | 100.0 | 2000: 94.76% | 0.94 |
| Sand | 78.9 | 83.3 | 83.3 | 83.3 | 89.3 | 75.8 | 89.2 | 78.9 | 83.3 | 80.0 | 80.0 | 83.3 | 83.3 | 92.2 | 2011: 92.84% | 0.92 |
| Mudflats with grass | 66.7 | 71.4 | 68.8 | 73.5 | 80.6 | 84.2 | 91.7 | 64.5 | 61.0 | 62.9 | 75.8 | 86.2 | 80.0 | 92.6 | 2021: 93.91% | 0.93 |
| Saltpan | 76.9 | 76.9 | 83.3 | 94.1 | 96.5 | 95.6 | 95.6 | 76.9 | 76.9 | 83.3 | 88.9 | 96.5 | 93.5 | 93.5 | | |

**Table 9** Correlation matrix for LULC class

| Correlations | | Waterbodies | Mangrove forest | Homestead vegetation | Agriculture | Mudflats | Sand | Mudflats with grass | Saltpan | Year |
|---|---|---|---|---|---|---|---|---|---|---|
| Waterbodies | Pearson correlation | 1 | − 0.844* | − 0.910** | 0.664 | 0.018 | 0.191 | − 0.070 | − 0.720 | − 0.932** |
| | Sig. (2-tailed) | | 0.017 | 0.004 | 0.104 | 0.969 | 0.681 | 0.881 | 0.068 | 0.002 |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Mangrove forest | Pearson correlation | − 0.844* | 1 | 0.853* | − 0.539 | − 0.470 | − 0.027 | − 0.128 | 0.662 | 0.865* |
| | Sig. (2-tailed) | 0.017 | | 0.015 | 0.212 | 0.287 | 0.954 | 0.785 | 0.105 | 0.012 |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Homestead vegetation | Pearson correlation | − 0.910** | 0.853* | 1 | − 0.839* | − 0.094 | − 0.320 | 0.352 | 0.671 | 0.989** |
| | Sig. (2-tailed) | 0.004 | 0.015 | | 0.018 | 0.842 | 0.484 | 0.439 | 0.099 | 0.000 |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Agriculture | Pearson correlation | 0.664 | − 0.539 | − 0.839* | 1 | − 0.290 | 0.746 | − 0.688 | − 0.716 | − 0.797* |
| | Sig. (2-tailed) | 0.104 | 0.212 | 0.018 | | 0.529 | 0.054 | 0.088 | 0.070 | 0.032 |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Mudflats | Pearson correlation | 0.018 | − 0.470 | − 0.094 | − 0.290 | 1 | − 0.635 | 0.528 | 0.085 | − 0.108 |
| | Sig. (2-tailed) | 0.969 | 0.287 | 0.842 | 0.529 | | 0.125 | 0.224 | 0.856 | 0.818 |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Sand | Pearson correlation | 0.191 | − 0.027 | − 0.320 | 0.746 | − 0.635 | 1 | − 0.721 | − 0.584 | − 0.307 |
| | Sig. (2-tailed) | 0.681 | 0.954 | 0.484 | 0.054 | 0.125 | | 0.067 | 0.169 | 0.503 |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Mudflats with Grass | Pearson correlation | − 0.070 | − 0.128 | 0.352 | − 0.688 | 0.528 | − 0.721 | 1 | 0.108 | 0.308 |
| | Sig. (2-tailed) | 0.881 | 0.785 | 0.439 | 0.088 | 0.224 | 0.067 | | 0.818 | 0.501 |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Saltpan | Pearson correlation | − 0.720 | 0.662 | 0.671 | − 0.716 | 0.085 | − 0.584 | 0.108 | 1 | 0.693 |
| | Sig. (2-tailed) | 0.068 | 0.105 | 0.099 | 0.070 | 0.856 | 0.169 | 0.818 | | 0.085 |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Year | Pearson correlation | − 0.932** | 0.865* | 0.989** | − 0.797* | − 0.108 | − 0.307 | 0.308 | 0.693 | 1 |
| | Sig. (2-tailed) | 0.002 | 0.012 | 0.000 | 0.032 | 0.818 | 0.503 | 0.501 | 0.085 | |
| | *N* | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed)

**Abbreviations**

BCCRF Bangladesh Climate Change Resilience Fund
BFD Bangladesh Forest Department
BFI Bangladesh Forest Inventory
CAD Coastal Afforestation Division
CBACC-CF Community Based Adaptation to Climate Change through Coastal Afforestation Project
BGB Belowground biomass
C-CROP Climate change resilience of place
CREL Climate resilient ecosystems and livelihoods
CRPARP Climate Resilient Participatory Afforestation and Reforestation Project
EbA Ecosystem-based adaptation
EbM Ecosystem-based mitigation
Eco-DRR Ecosystem-based disaster risk reduction
FAO Food and Agriculture Organization
GEE Google Earth Engine
GI Green infrastructure
GoB Government of Bangladesh
ISODATA Iterative Self-Organizing Data Analysis
IUCN International Union for Conservation of Nature
LDC Least developed countries
LULC Land use and land cover
MFF Mangrove for future
MoEFCC Ministry of Environment, Forest and Climate Change
NBS Nature-based solution
NDVI Normalized Difference Vegetation Index
RF Random forest
SDSS Spatial Decision Support System
SEALS Sundarbans Environment and Livelihood Security
SRF Sundarban Reserve Forest
SUFAL Sustainable forests and livelihoods
TD Transform divergence
TOA Top of atmosphere
UNDP United Nations Development Program
USAID United States Agency for International Development
USD US dollar
UTM Universal Transverse Mercator
USGS United States Geological Survey

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RM: conceptualization, data acquisition, field visit, formal analysis, writing; LZ: conceptualization, data interpretation, writing, funding; GL: review and editing. All authors read and approved the final manuscript.

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Not applicable.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare that they have no competing interests.

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