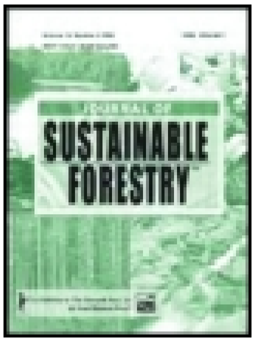

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Mangrove management for climate change adaptation and sustainable development in coastal zones

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ABSTRACT

Due to their prevalence in developing countries and the range of ecosystem services they provide, projects aimed at promoting mangroves align with several of the UN Sustainable Development Goals—specifically Goals 13, 14, and 15—which concern adaptation to climate change and the sustainable management of forest and coastal resources. Although mangroves themselves are sensitive to climate change, they also provide services that would help reduce damages, by sequestering carbon, enhancing coastline stability, and protecting coastal settlements from tropical storm surges. In particular, mangroves can rapidly colonize and stabilize intertidal sediments, promoting coastal accretion to reduce the impact of sea level rise. The Government of Bangladesh has established mangrove plantations with the intent to accelerate accretion and stabilize 120,000ha of coastland. As a case study, this paper uses GIS data on coastal dynamics and land cover to evaluate the effectiveness of mangrove plantations for facilitating accretion and preventing erosion in Bangladesh. The results indicate that plantation areas experience greater rates of accretion relative to erosion than non-plantation areas, confirming that mangroves have an important role to play in the sustainable development of coastal regions.

KEYWORDS

Bangladesh; climate change adaptation; coastal erosion; ecosystem service; land accretion; mangrove plantation; Sustainable Development Goals

Introduction

Mangroves are coastal and riverside forests that thrive at interfaces between land and sea in the tropics and subtropics. There currently exists approximately 14 to 15 million hectares of mangroves distributed across 124 countries, most extensively in developing countries in Asia (Food and Agriculture Organization [FAO], 2007; Giri et al., 2011). These ecosystems provide a wide range of goods and services, such as forestry products, fisheries, and non-timber forest products (Agrawala et al., 2005; FAO, 2007; McLeod & Salm, 2006). Other services include flood and erosion control, coastal stabilization, nurseries for marine fisheries, storm protection, and pollution filtering.

Mangrove management projects align with several of the United Nations Sustainable Development Goals (SDGs) (United Nations General Assembly, 2015). These include Goal 13: “Take urgent action to combat climate change and its impacts” (p. 23); Goal 14: “Conserve and sustainably use the oceans, seas and marine resources for sustainable development” (p. 23); and Goal 15: “Sustainably manage forests, combat desertification,

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halt and reverse land degradation, halt biodiversity loss" (p. 24). Mangrove management addresses the first and second targets of Goal 13: to "strengthen resilience and adaptive capacity to climate-related hazards and natural disasters" and to "integrate climate change measures into national policies, strategies, and planning" (p. 23). Also germane is the second target of Goal 14: to "sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts" (p. 23). While mangrove management is related to several targets under Goal 15, it most directly addresses the second: to "promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests, and substantially increase afforestation and reforestation globally" (p. 24).

As a coastal forest ecosystem, the role of mangroves in achieving SDGs 14 and 15 is self-evident. This paper focuses on SDG13, since mangrove management is unique among climate strategies in that it can provide both mitigation, through the sequestration of carbon, and adaptation, through stabilizing shoreline erosion, reducing storm surges, and preventing inland soil salinization. Mangroves are prevalent in developing countries more vulnerable to climate change. Seeking to protect coastal communities, countries anticipating sea level rise (SLR) and more powerful tropical storms due to climate change have undertaken projects aimed at preserving, restoring, and afforesting mangroves. For example, Bangladesh has long recognized the importance of mangroves and has successfully established over 50,000ha of mangrove plantations (Chow, 2015). Nine other least developed countries prioritize mangroves in their National Adaptation Programs of Action (UNFCCC, 2016). Despite such efforts, urban development, conversion to cultivation, and over-harvesting of wood products have resulted in deforestation rates of 1–2% per year—equivalent to about one-third of mangroves worldwide over the past 50 years—with the greatest losses occurring in the Indo-Malay Philippine Archipelago (Alongi, 2002; Duke et al., 2007; Hidayati, 2000; Polidoro et al., 2010).

This paper provides an overview of mangrove preservation, rehabilitation, and plantation projects as mitigation and adaptation strategies for developing countries to cope with climate change, in accordance with SDG13. The following sections review the potential climate change impacts on mangroves; their carbon sequestration capability and emissions from their destruction; and the ecosystem services that may ameliorate climate change damages. As an example, this paper also evaluates an illustrative case study concerning Bangladesh and its use of mangrove afforestation as a strategy for coastal land stabilization in its efforts to adapt to climate change.

Climate change impacts on mangroves

To help achieve SDG13, mangroves will need to be sufficiently resilient to climate change. Geological evidence suggests that mangroves have adapted to previous changes in climate and sea level (Alongi, 2015; Ellison & Stoddart, 1991; Field, 1995; Krauss et al., 2014; Parkinson, DeLaune, & White, 1994; Woodroffe et al., 2016). However, some mangrove species also occur in conditions that approach ecological tolerance limits, with mortality observed following minor variations in hydrological or tidal regimes (Blasco, Saenger, & Janodet, 1996).

The Earth warmed 0.65–1.06°C between 1880 and 2012 and will likely warm another 1.1–3.1°C by 2100 even when assuming stabilization scenarios (Intergovernmental Panel on Climate Change [IPCC], 2013). The temperature increase will favor expanded latitudinal ranges of mangroves—via the displacement of salt marshes—but with altered species composition (Alongi, 2002, 2015; Godoy and De Lacerda, 2015; Saintilan, Wilson, Rogers, Rajkaran, & Krauss, 2014). Range expansion would be limited by man-made barriers and by mortality due to extreme winter freeze events, as mangroves are most likely to disperse where temperatures are buffered by large expanses of water and saturated soil (Cavanaugh et al., 2013; Osland et al., 2017). The warming expected over the next century lies within the diurnal oscillation for many mangrove species, which can exceed 20°C, and thus, warming alone is not expected to adversely impact mangroves (Field, 1995; McLeod & Salm, 2006). Likewise, increased atmospheric CO_2 may enhance productivity, though the limited data suggest that not all species will respond similarly (Alongi, 2002; Edwards, 1995; Field, 1995).

Decreases in mean precipitation pose a greater threat to mangroves, which are adapted to a specific balance of fresh and saline water. Global precipitation rates are expected to increase unevenly, with increases and decreases in different regions. A decrease in rainfall (e.g., during winters in Central America and Australia) would reduce freshwater surface runoff and groundwater input to mangroves, resulting in increased soil salinity, decreases in productivity, growth, and seeding survival, and shifts to more salt-tolerant species (McLeod & Salm, 2006).

The intensity of precipitation events and the frequency of major cyclonic storms, resultant surges, and floods are also projected to increase, especially in the tropics (IPCC, 2013). In North America, Africa, and Asia, mass mangrove mortality has been observed following storms that uproot trees and leave soil vulnerable to erosion (FAO, 2007; McLeod & Salm, 2006). Increased tropical storm activity would also likely accelerate saline intrusion into coastal soils (Agrawala et al., 2005). Rapid sea level rise (SLR), the most problematic climate impact, will exacerbate inundation, salinity stress, and erosion, possibly causing mangroves' margins to retreat landwards (Friess, 2015; Gilman et al., 2006). If landward transgression is obstructed by human land uses, then the retreating mangrove could revert to a narrow fringe or be lost entirely.

However, mangroves possess characteristics that would help them adapt. They trap fluvial sediment from upstream sources and decaying litter fall, which accumulates as peat or mud and gradually elevates the soil substrate. Even under potential stabilization scenarios, global mean sea level is projected to rise 0.32–0.63m by 2100, or approximately 3.3–6.6mm per year (IPCC, 2013), with varying local rates (Krauss et al., 2014). These rates can exceed the vertical accretion observed in studies of mangrove peat cores and surface elevation measures, suggesting that some mangroves may not be able to keep pace with accelerated SLR (Lovelock et al., 2015; Sasmito, Murdiyarso, Friess, & Kurnianto, 2015). Resilience to SLR depends on site-specific conditions such as hydrodynamic factors, sediment inputs, plant productivity, and subsidence rates (Woodroffe et al., 2016). For example, limited sediment sources on Pacific low islands result in accretion rates of 0.8mm per year; mangroves there can tolerate under stress a SLR of only 0.9–1.2mm per year (Ellison & Stoddart, 1991). Mangroves on high islands are more resilient and can keep pace with rates of SLR up to 4.5mm per year, depending on the sediment supply (Ellison, 2000a). Mangroves in continental estuaries and deltas are more likely to keep pace with SLR thanks to the large volumes of sediment they receive (Agrawala et al., 2005). Cleared areas are prone to decreases in surface elevation, whereas rehabilitated mangroves have demonstrated increases at relatively high vertical accretion rates (Sasmito et al., 2015). However, other human activities, such as restrictions of upstream flows and groundwater extraction, can reduce accretion or increase subsidence, rendering mangroves more vulnerable to SLR (Woodroffe et al., 2016).

Climate-related damages to mangrove ecosystems also threaten human communities that rely on them for subsistence livelihoods. For example, traditional agriculture and fisheries in Bangladesh associated with the Sundarban mangrove system are well adapted to the tidal and seasonal variation in salinity levels moderated by the mangroves (Agrawala et al., 2005). Many coastal communities become trapped in a positive feedback loop of poverty, lack of livelihood choices, and over-exploitation of natural resources, resulting in degradation of the subsistence resource base and deeper impoverishment (King & Adeel, 2002). For instance, the clearing of mangroves for intensive shrimp aquaculture in central coastal Vietnam led to water pollution, pond failures, and indebtedness among farmers who invested heavily into this enterprise (Hui & Scott, 2008). Lifestyles dependent on mangrove ecosystems are often under additional pressure from conversion to aquaculture and other threats such as excessive logging, water diversion, and urban development. Government policies that encourage these activities often exacerbate the vulnerability of these communities to climate change (Adger, 1999).

Carbon sequestration and emissions

The high carbon (C) content of mangrove forests suggests that their stocks and fluxes should be integrated into national GHG accounting in accordance with Target 2 of SGD13. Mangroves can store carbon at greater densities than other forest types (Winrock International, 2014); thus, deforestation not only generates emissions, but also removes highly productive fixers of atmospheric C. Mangroves fix organic C well in excess of ecosystem needs for respiration, with excess photosynthetic C representing approximately 40% of net primary production (Duarte & Cebrian, 1996). The global average net primary productivity, combining leaf litter, root, and wood production, has been estimated to be approximately 1.8tC/ha-yr (Kristensen, Bouillon, Dittmar, & Marchand, 2008). Carbon accumulates in both tree wood and peat, and mangroves can sequester C at a rate of 1.5tC/ha-yr (Gong & Ong, 1990), with belowground biomass constituting 10–55% of the total biomass (Kristensen et al., 2008). Belowground sequestration rates in natural mangroves can vary from 0.15 to 2.24tC/ha-yr, and sequestration rates in mangrove plantations can exceed 6tC/ha-yr (Fujimoto, 2004). Globally, mangroves store an estimated $16*10^7$tC/yr in biomass and $2*10^7$tC/yr in sediment (Duarte, Middelburg, & Caraco, 2005; Twilley, Chen, & Hargis, 1992). The expansion of mangrove latitudinal ranges—as fewer freezing events fosters their supplanting of salt marshes—could bolster terrestrial C storage and exert a negative feedback on warming (Doughty et al., 2016).

On the other hand, late in the last century, nearly 50,000 square km of mangroves were lost to deforestation, releasing an estimated $3.8*10^8$tC stored as standing biomass (Cebrian, 2002). This number substantially underestimates the total carbon emissions from mangrove deforestation because it ignores belowground and detrital biomass. Due to high density below-ground storage, mangroves are among the most carbon-rich forests in the tropics, containing on average 1,023tC/ha in the Indo-Pacific region (Donato et al., 2011). However, the C density of mangroves varies dramatically by location (Hutchison, Manica, Swetnam, Balmford, & Spalding, 2014). Within Sulawesi, Indonesia alone, the total ecosystem C density can range from 415tC/ha in oceanic mangroves to 2203tC/ha in estuarine mangroves. The C densities of other mangroves worldwide lie within this range, with the density below-ground often greater than above-ground by an order of magnitude (Donato et al., 2011; Murdiyarso et al., 2015). Logging or conversion to agriculture can decrease the above-ground C density of biomass by at least 50% (Lasco & Pulhin, 2003). Conversion to aquaculture requires the excavation of at least 2 meters of sediments of high C content, so digging ponds can release another 70tC/ha-yr (Ong, 2002).

Given their capability and capacity for C sequestration, mangroves are potentially well-suited for generating monetary compensation from reduced emissions from deforestation and degradation (REDD+) (Murdiyarso et al., 2015). In practice, the inclusion of mangroves into REDD+ requires consideration of uncertainties regarding primary productivity, carbon fluxes, and coastal morphodynamics (Alongi, 2011).

Ecosystem services and climate change adaptation

Aside from C sequestration, mangroves produce a variety of other valuable goods and services that benefit local communities. These include services that increase climate resilience as mandated by the first target of SDG13, such as shoreline stabilization and storm protection.

Mangroves can colonize intertidal sediments and promote further vertical accretion and stabilization (Lee et al., 2014). Soil surface dynamics are mediated by both physical (e.g., water flux, inorganic sedimentation) and biological (e.g., plant debris deposition, root accumulation) processes. Extensive aerial root structures help keep soils compact and slow erosion, with the four different types—prop roots, pneumatophores, knee roots, and plank roots—varying in their effectiveness in retaining sediments (Krauss et al., 2014). By increasing sedimentation, reducing wave exposure, and forming peat, mangroves can accelerate land maturation and help mitigate vulnerability to tropical storm surges and SLR. For example, the mangroves of French Guiana help trap the sediments flowing through the mouth of the Amazon River (FAO, 2007). Researchers also have demonstrated that mangrove deforestation caused large-scale erosion in Vietnam (Mazda et al., 2002). Mangrove afforestation can reverse this effect, and plantations in Bangladesh have been used to help stabilize 120,000 hectares of coastland (Saenger & Siddiqi, 1993). Similar restoration programs have been underway in other areas prone to coastal erosion, including in Australia, Thailand, Vietnam, the Philippines, and Benin (Blasco et al., 1996). Results have been mixed, but suggest that plantations can play a vital role towards ecological rehabilitation (Bosire et al., 2008; Ellison, 2000b).

Many countries in South and Southeast Asia also have been increasingly undertaking restoration and preservation of coastal greenbelts as protection against tropical cyclones. Areas sheltered by mangrove forests experience less damage than non-forested areas (Ali, 1996), and mangrove tree species are more resilient to cyclone damage than non-mangrove species (Saenger & Siddiqi, 1993). Mangroves provide storm protection by dissipating and reducing the huge wave energies that occur during storms and typhoons. Their thickly grown leaves and dense networks of trunks, branches, and above-ground roots create drag forces that significantly reduce wave period and height (Mazda, Magi, Ikeda, Kurokawa, & Asano, 2006; Mazda, Magi, Kogo, & Hong, 1997; Quartel, Kroon, Augustinus, Van Santen, & Tri, 2007).

However, their effectiveness in storm protection can be attenuated by habitat degradation, or, in plantations, insufficient age (Dahdouh-Guebas et al., 2005; Mazda et al., 1997). Hence, mangrove shelterbelts can provide protection only if appropriately designed and managed. Degraded mangroves can provide less shelter than expected by local inhabitants, creating a false sense of security. Moreover, nations promoting efforts to utilize mangroves for storm protection must take into account the fact that the ecosystem itself is threatened by climate change and, therefore, must consider alternate or complementary adaptation strategies where appropriate.

Case study: Coastline stabilization in Bangladesh

Mangrove plantations and climate change adaptation in Bangladesh

Socioeconomic, geographical, and climatic characteristics make Bangladesh one of the countries most vulnerable to the damaging impacts of climate change (Agrawala, Ota, Ahmed, Smith, & Van Aalst, 2003; Ministry of Environment and Forest of the Government of Bangladesh [MoEF GoB], 2007). Bangladesh is economically underdeveloped, with an average per capita income less than the average for other South Asian countries, and more than a third of its population lives in poverty. Situated at the end of the Ganges-Brahmaputra-Meghna (GBM) river system, Bangladesh is largely composed of alluvial delta extremely prone to flooding, storm surges, and rapid geomorphological changes (Brammer, 2014). Bangladesh also receives the brunt of tropical monsoons and cyclones which funnel northward through the Bay of Bengal. Between 1991 and 2000, Bangladesh experienced 93 major disasters resulting in nearly 200,000 deaths and causing US$5.9 billion in damages with high losses in agriculture and infrastructure (MoEF GoB, 2007). SLR and a greater frequency of extreme weather events will increase coastal inundation, erosion, and saline intrusion, threatening poor households, coastal infrastructure, and agricultural productivity.

Since 1966, the Government of Bangladesh (GoB) has created mangrove plantations on newly accreted lands, or *chars*, in the coastal zones of Barisal and Chittagong Divisions as a defense against storm surge and to stabilize shorelines (Figure 1) (Iftekhar & Islam, 2004). The two main species used, *Sonneratia apetala* and *Avicennia officinalis*, are pioneers with pneumatophore morphology which establish well in low elevation zones (Sasmito et al., 2015). After assigning jurisdiction over 497,976ha of *chars* to the Bangladesh Forest Department (BFD) in 1976 (Islam, 2000), the GoB, with financing from the World Bank (Saenger & Siddiqi, 1993; World Bank, 2013), established approximately 148,500ha of mangroves by 2001 (Iftekhar & Islam, 2004). However, erosion and encroachment by settlements following land stabilization have destroyed most plantation attempts, especially in Chittagong Division where rapid accretion rendered areas suitable for conversion to agriculture. About 45,000ha of mature plantations remained in 2007, with the plantations in Barisal Division mostly intact (BFD, MoEF, Bangladesh Space Research and Remote Sensing Organization & Ministry of Defense, 2007).

Aligning with SDG13, the BFD continues to establish new plantations as part of a mitigation and adaptation strategy in response to climate change, according to the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) (United States Department of State, 2014) and the National Adaptation Plan (Bangladesh Ministry of Environment and Forest, 2009). The Strategic Program for Climate Resilience aims to

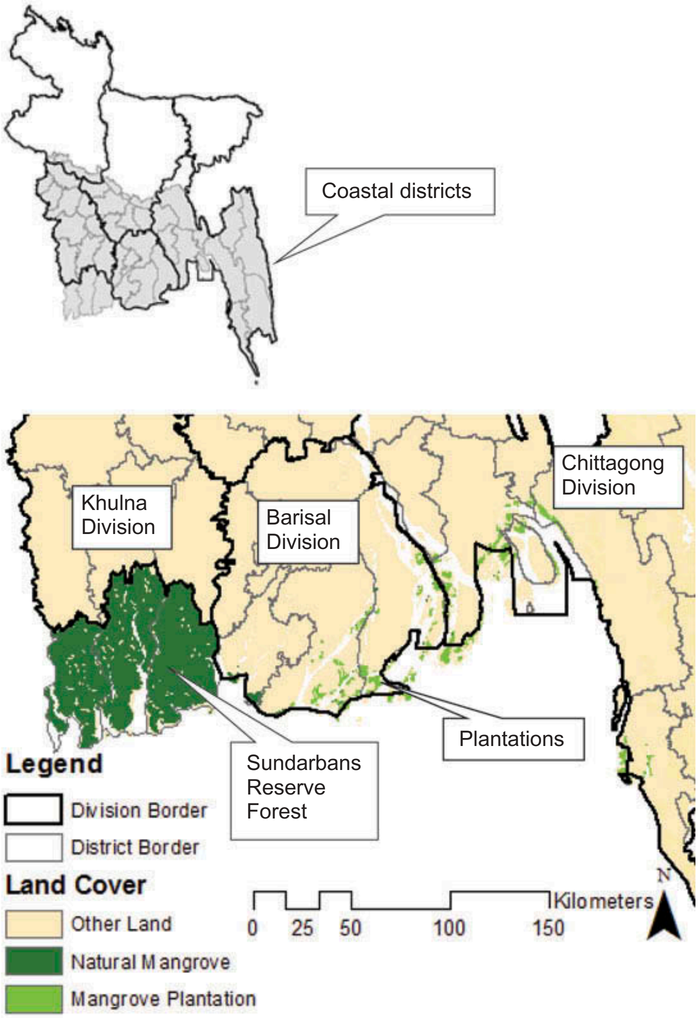

Figure 1. Map showing Sundarbans Reserve Forest and extent of mangrove plantations. Land cover information provided by the Center for Environmental GIS.

afforest 300ha on the seaward side of coastal embankments by 2020 (Forni, 2015; GoB, 2010). Additionally, the Community-Based Adaptation to Climate Change through Coastal Afforestation program afforested 9000ha of mangroves between 2009 and 2014 (United Nations Development Program [UNDP], 2011; P. Nandy, personal communication, 11 November 2015), and the Climate Resilient Participatory Afforestation and Reforestation Project plans to establish 5700ha of new mangroves (World Bank, 2013).

Although the Forest Department prohibits the felling of whole trees, these plantations are the sources of other ecosystem services for coastal villages, through the provision of fuelwood and other goods that constitute substantial value to these communities (Chow, 2015). However, the provision of regulating ecosystem services by these plantations, such as storm surge protection and erosion control, is not robustly supported by available empirical evidence. The lack of systematic and routine inventory and monitoring data in Bangladesh has complicated project assessment (World Bank, 2013). Econometric analyses suggest that any protective function against tropical storms imparted by the plantations generally has not been observable in agricultural and aquaculture production data (Chow, 2016). Moreover, the characteristics which determine the amount of protection are not well understood (Lee et al., 2014). However, anecdotal evidence suggests that the role of plantations in facilitating the stability of coastal land is potentially more promising (Iftekhar & Islam, 2004; Saenger & Siddiqi, 1993), though empirical studies often focus on only small areas limited in scope (e.g., Shaifullah, Mezbahuddin, Sujaiddin, & Haque, 2008). This case study compares erosion and accretion outcomes on coastal land that have mangrove plantations with lands which do not, using data derived from satellite remote sensing covering the entire plantation zone. Via GIS analysis, this case study provides evidence that mangroves in Bangladesh have contributed to enhancing erosion control and land accretion.

Methodology

The study area (20.7–23.0°N, 89.9–92.4°E) encompasses the Tentulia, Meghna, and Feni River estuaries and nearby deltaic islands, spanning the entire plantation zone in Barisal and Chittagong Divisions (Figure 1). Settlers removed almost all of the natural vegetation of this region over a century ago, and thus, the plantations are the only remaining dense vegetation cover (A. Nishat, personal communication, June 2, 2009). Coastal Bangladesh experiences slightly unequal semidiurnal tides, with a terrain generally at or near sea level; tidal heights vary, with tidal ranges reaching 3 meters at the spring equinox (FAO, 1985).

Historically, reliable recordkeeping—on where and when new and supplementary plantings have taken place—has been poor over most of the course of Bangladesh's mangrove plantation programs. There also has been a lack of large-scale follow-up data regarding the results of plantation activities, such as vegetation density and soil accretion, which makes coarser remote sensing-based approaches necessary. To capture the morphodynamics of coastal accretion and erosion, this study uses a GIS dataset created by the Bangladesh Space Research and Remote Sensing Organization (SPARRSO) from LANDSAT MSS imagery recorded in late January and early February of 1973 (60m pixel resolution), LANDSAT TM imagery recorded in January 1989 (30m resolution), and LANDSAT TM imagery recorded in January and March of 2010 (30m resolution) (Sarker, 2013). To encompass the entire area of interest, the following four data frames were used: 136/44, 137/44, 136/45, and 137/45. All data frames were recorded between 9:40AM and 10:40AM to coincide with morning high tides. Image processing was calibrated against tidal data at the date and time of each image capture at four tide gauges: Ramdaspur (22.80°N, 90.65°E), Char Changa (22.22°N, 91.05°E), Lohalia River (22.97°N, 90.50°E), and Sandwip (22.44°N, 91.46°E). Classification methodology is detailed by Sarker (2013), and outputs were verified by visual interpretation of satellite imagery.

The resultant dataset identifies land areas which accreted (i.e., newly exposed at high tide) or eroded (i.e., newly submerged at high tide) within two time periods: 1973 to 1989 and 1989 to 2010. These specific intervals were selected due to availability of unobstructed imagery for all data frames, which needed to also correspond with high tides, as well as span long enough periods to capture observable coastline changes. The first period roughly includes the earliest plantation efforts through the completion of the first major official development assistance-funded plantation effort, Mangrove Afforestation Projects I and II. The second period evaluates the outcome of the surviving plantations from previous efforts, as well as the Forest Resources Management Project and other efforts implemented prior to 2010.

This study also utilizes coastal land cover classification data from 2001 which identifies 66,000ha of mangrove plantations, created by the Center for Environmental Geographic Information Systems (CEGIS) from LANDSAT ETM+ and LANDSAT TM imagery (30m resolution) recorded in January 2001 during the dry season when the denser plantation cover is distinct from any cultivated land. Classifications were verified by visual interpretation of satellite imagery. I included a fifty meter buffer to account for accretion and erosion, beyond the immediate plantation boundaries, which may still be impacted by their presence.

Using ArcGIS 10 software (Esri, Redlands, CA, USA), I overlaid the land cover data identifying mangrove plantations over the dataset depicting changes in accretion and erosion, and calculated the areas within each change category (Figure 2). From this information, I calculated the ratio of erosion to accretion for both time periods for mangrove and non-mangrove (i.e., primarily mudflats, settlements, and agriculture) areas, in order to make comparisons that are independent of scale. Since the BFD selects plantation sites on *chars*, which may be undergoing some accretion even in the absence of mangroves, I also investigate the outcomes in 2010 of planted and unplanted land which was newly accreted between 1973 and 1989. This analysis comprehensively covers the entire plantation zone.

Results and discussion

About 118,000ha of new land accreted in Bangladesh from 1979 to 1989, with around the same amount forming between 1989 and 2010 (Table 1 and Figure 2). Approximately 54,500ha eroded during the first period, and 79,000ha eroded in the second. In both periods, Chittagong Division—particularly mainland Noakhali District, Urirchar island, Nijhum Dwip

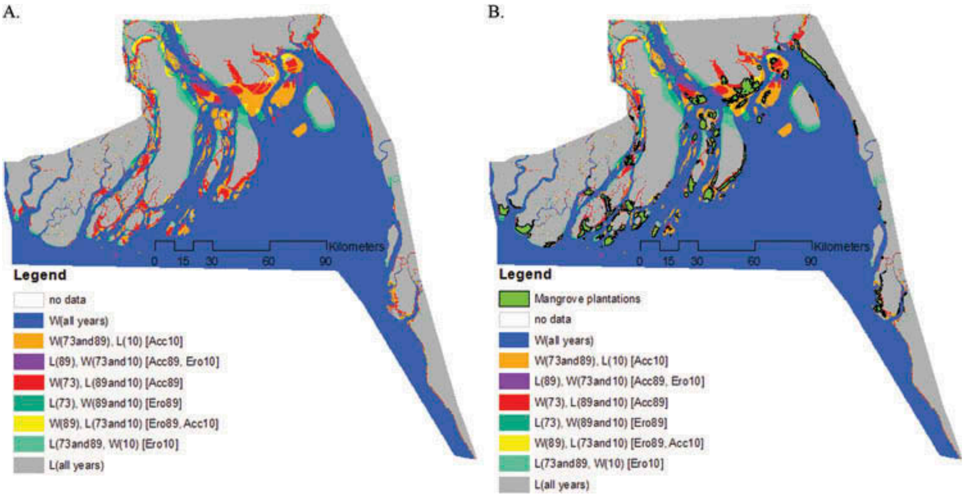

Figure 2. A) Coastal morphodynamics in Barisal and Chittagong Divisions from 1973 to 2010. Data from SPARRSO. B) Mangrove areas in 2001 overlaid on A). W = water. L = land. Years in parentheses. Observed land change (Acc = accretion; Ero = erosion) in brackets.

Table 1. Hectares of land accreted or eroded in plantation and non-plantation areas.

	1973–1989 all land	1973–1989 plantation	1973–1989 non-plantation	1989–2010 all land	1989–2010 plantation	1989–2010 non-plantation
Both divisions						
Accretion	117,848	30,933	86,916	118,477	17,425	101,052
Erosion	54,532	832	53,701	79,177	3,698	75,479
Ratio	2.2	37.2	1.6	1.5	4.7	1.3
Barisal Division						
Accretion	52,860	12,718	40,141	50,578	7,587	42,991
Erosion	31,680	312	31,369	42,082	1,779	40,303
Ratio	1.7	40.8	1.3	1.2	4.3	1.1
Chittagong Division						
Accretion	64,989	18,214	46,775	67,899	9,838	58,061
Erosion	22,852	520	22,332	37,095	1,918	35,176
Ratio	2.8	35.0	2.1	1.8	5.1	1.7

island, and the southern end of Hatiya island—experienced more accretion than Barisal. More land eroded in Barisal, mainly on parts of Char Fasson Island adjacent to the Meghna River. In Chittagong Division, erosion largely occurred on the northern end of Hatiya Island and on Sandwip Island. Hossain, Dearing, Rahman, and Salehin (2016) also report net accretion in the Meghna estuary, whereas, to the west, net erosion has occurred in the coastal Sundarbans during the same time period (Rahman, Dragoni, & El-Masri, 2011).

The results suggest that, compared to unplanted areas, mangrove plantations have promoted accretion while mitigating erosion in coastal Bangladesh. Between 1973 and 1989, plantation areas experienced 37.2 times more accretion than erosion, compared to only 1.6 times in non-plantation areas (Figure 3 and Table 1). From 1989 to 2010, plantation areas underwent only 4.7 times more accretion relative to erosion, whereas non-plantation areas experienced 1.3 times more accretion than erosion. Therefore, in both periods, gains in new land formation were greater than losses from erosion in all zones, but plantation areas achieved far greater rates of accretion relative to erosion than non-plantation areas.

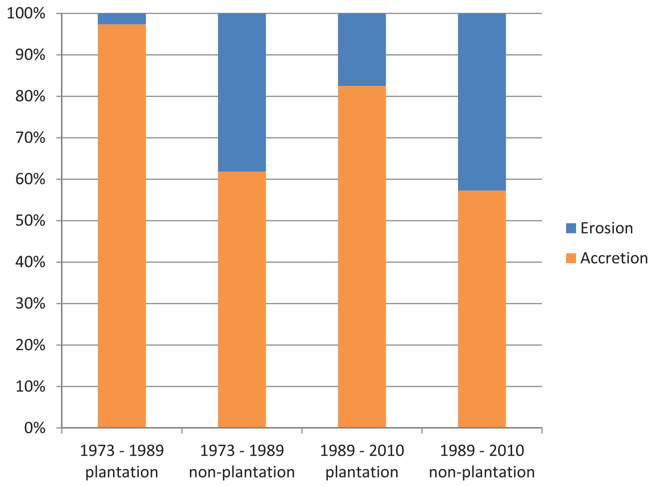

Figure 3. Accretion relative to erosion, scaled to 100% for both time periods, in plantation and non-plantation areas.

The above result, however, does not necessarily confirm a causal link between mangrove plantations and coastal land stabilization, since it could suggest instead that the BFD is merely skilled at identifying areas to plant which are undergoing the process of net positive accretion. Thus, it is instructive also to consider the fate of lands which are identified as newly accreted in 1989. When considering these areas only, 31% of non-plantation land had eroded by 2010, whereas in comparison, only 10% of plantation had eroded (Figure 4 and Table 2). Combined with the accretion-to-erosion ratios reported above, these results strongly indicate that mangrove plantations in Bangladesh have contributed to coastal land stabilization and erosion control, an important ecosystem service in light of expected SLR and increased intensity of tropical storm surges due to climate change.

Although studies of land accretion in anthropogenic mangrove plantations are rare, these results accord with other research on these and natural mangroves. Shaifullah et al. (2008), investigating the soil impacts from mangrove afforestation in Lakshmipur, Bangladesh, report that plantation areas consistently have higher soil particle densities at multiple depths compared to barren areas, in both seaward and inland zones. Plantation areas also exhibit consistently higher soil organic carbon and greater silt and clay content relative to sand particles, which altogether indicates that the plantations have positively contributed to soil binding. In another South Asian example, Kumara, Jayatissa, Krauss, Phillips, and Huxham (2010) find that among experimental mangrove plantations in Sri Lanka, greater planting densities yield higher rates of accretion. Similarly, McKee (2011) reports that natural Caribbean mangroves with high root densities tend to experience an increase in elevation, whereas those with low root densities tend to experience a decrease. Thampanya, Vermaat,

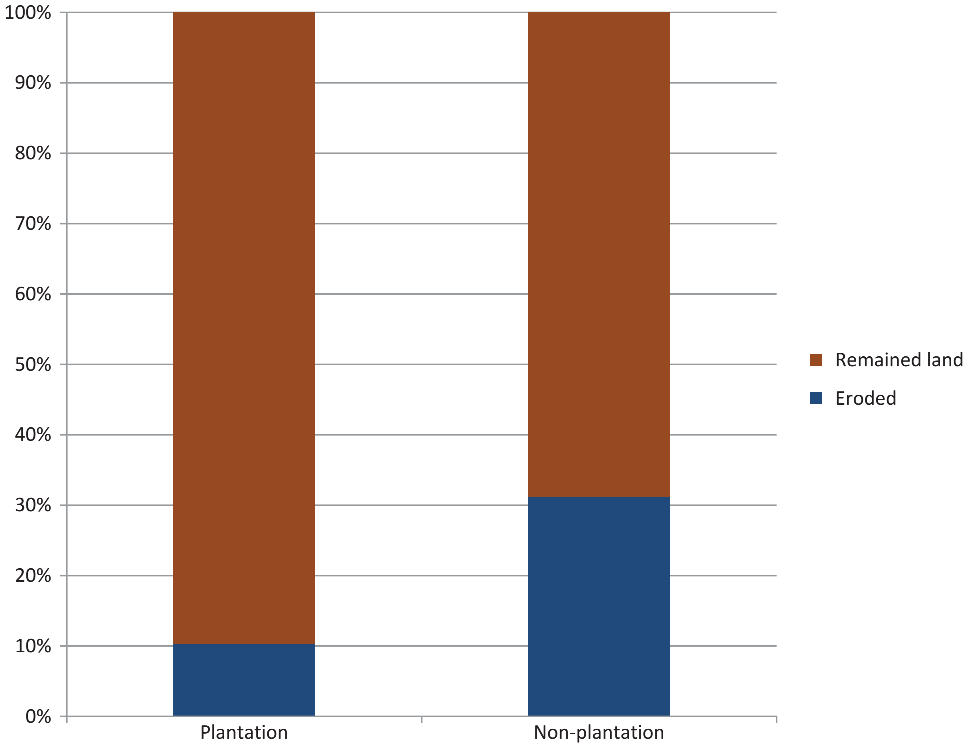

Figure 4. Outcome in 2010 of land which was newly accreted in 1989, plantation and non-plantation.

Table 2. Hectares of land, newly accreted in 1989, which eroded or remained land in 2010.

	all land	plantation	non-plantation
Both divisions			
Remained land	87,532	27,739	59,793
Eroded	30,317	3,193	27,123
Ratio	2.9	8.7	2.2
Barisal Division			
Remained land	39,895	11,324	28,572
Eroded	12,964	1,395	11,570
Ratio	3.1	8.1	2.5
Chittagong Division			
Remained land	47,637	16,416	31,221
Eroded	17,352	1,799	15,553
Ratio	2.8	9.1	2.0

Sinsakul, and Panapitukkul (2006) also report that the presence of mangroves is associated with greater accretion and reduced erosion in the coastal areas of southern Thailand. Aside from plant and root densities, accretion rates in mangroves also depend on their geophysical location relative to local hydrological characteristics (Lynch, Meriwether, McKee, Vera-Herrera, & Twilley, 1989), functional root type (Krauss, Allen, & Cahoon, 2003), and sediment availability (Agrawala et al., 2005; Ellison, 2000a; Ellison & Stoddart, 1991).

Hydrological and hydrodynamic conditions are also primarily responsible for coastal erosion in Bangladesh. Heavy discharge currents through the GBM river system, wave action created by strong southwest monsoon winds, high astronomical tides, and tropical storm surges all immediately contribute to coastal erosion (Ali, 1999). SLR—currently about 1.06 to 1.75 mm per year in the North Indian Ocean (Unnikrishnan & Shankar, 2007)—will also exacerbate erosion with a comparatively subtle but long term impact over the course of the next century.

Coastal mangrove plantations can help mitigate these impacts, but optimizing site selection and management remains a challenge due to lack of information regarding the local hydrodynamic, hydrological, and socioeconomic drivers of accretion and erosion, and more research on these phenomena is necessary. Because the policy goal is the creation and maintenance of contiguous barriers to protect coastal inhabitants and property (Iftekhar & Islam, 2004), natural risks to the plantations themselves are often not primary concerns. Shoreline stabilization and prevention of erosion are important ecosystem services provided by mangrove plantations to the dense populations of rural poor living in coastal Bangladesh. By mitigating the potential loss and damage caused by climate change-induced SLR and storm surges, the preservation, restoration, and afforestation of mangrove forests therefore have an important role to play in sustainable development here and in other tropical coastal zones.

Concluding remarks

When the suite of local ecosystem services is considered, regardless of the services relevant to climate change and SDG13, the benefits of mangrove management to coastal communities can exceed its costs, particularly in developing countries where the costs of labor and other inputs are low (Chow, 2016). Mangrove conservation, restoration, and afforestation are well-suited to help tropical countries with compatible coastlines achieve SDG14 and 15, which pertain to the sustainable management of coastal and forest ecosystems, respectively.

Unfortunately, in many countries where mangroves are threatened, their public, non-marketed ecosystem services do not factor into individual decisions regarding their best use. The private calculus that ignores public benefits results in overexploitation of harvestable commodities such as fuelwood or excessive conversion to other land uses like agriculture and aquaculture. In some settings, mangrove loss is driven further by the disproportionate influence of politically well-connected agents who benefit from logging or development at the expense of more vulnerable groups (Allen, 2006). Rates of mangrove loss are slowing, though, as countries increasingly recognize their value and undertake conservation and restoration policies (FAO, 2007). For example, current policy in Bangladesh requires that 25 years after establishment half of mangrove plantation lands remain as reserve forest, while the other half is returned to the Land Ministry for distribution by local administrations (World Bank, 2013). Any conversion of mangroves to cultivation requires approval from the Ministry of Environment and Forests.

Mangrove preservation and plantation also represent promising strategies both to mitigate atmospheric C as well as to help coastal communities in developing countries weather the damages of climate change, in accordance with SDG13. The United Nations Sustainable Development Solutions Network (SDSN) has proposed that GHG fluxes from managed forests be an indicator for progress on SDG13 (United Nations General Assembly, 2015). Mangrove management projects, which are already frequently funded through bilateral and multilateral aid, should be included in climate financing that is incremental to official development assistance, another SDG13 indicator proposed by the UN SDSN. International interventions to place a monetary value on sequestered carbon, such as REDD+, could enhance the ability of developing countries to conserve these important resources. There exist, however, legitimate reasons to caution against promoting mangroves as an ideal mitigation strategy. Mangroves themselves are under substantial threat from climate change, and thus, they may be riskier sequesters of carbon than other ecosystems like tropical rainforests. The permanence of stored carbon is a significant concern where pressures such as storms, SLR, and increased salinity endanger their survival. These risks also complicate efforts to use mangroves to participate in carbon markets. Hence, efforts to increase or sustain mangrove areas may require strategies such as river enhancement to increase freshwater flows and guided sedimentation to augment accretion and lessen the possibility of future subsidence. Such supplementary initiatives would entail additional costs that could make mangrove promotion a less attractive alternative to other mitigation measures.

Likewise, mangrove promotion has been to date an imperfect adaptation strategy due to lack of knowledge and experience. Some rehabilitation and restoration projects have had mixed results, attributed to inadequate site selection, improper soil preparation and planting techniques, and low diversity in species selection (Alongi, 2002). When inappropriately managed, mangroves of suboptimal height, density, or species composition could harm adjacent communities by providing a false sense of security against extreme weather events. Adequate training of coastal managers, adaptive plantation strategies, information sharing, capacity building, and additional research are therefore necessary for mangrove projects to successfully provide climate protection and facilitate the sustainable development of coastal areas.

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