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ESTIMATION OF CHANGE IN ABOVEGROUND BIOMASS IN FOUR NATIONAL FORESTS IN BANGLADESH

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ABSTRACT

Forest biomass helps mitigate climate change impacts through the sequestration of atmospheric carbon dioxide and potentially storing it for long periods. Deforestation and unsustainable timber harvesting cause the reduction of forest biomass, resulting in the reduced carbon sequestration capacity and altered natural balance of forest ecosystems. We used Landsat 8 Operational Land Imager (OLI) to compare the aboveground forest biomass (AGB) changes between 2014 and 2020 for the four national forests that represent important forest cover zones in Bangladesh. We found no considerable change in AGB in the Sundarbans mangrove forest and the Ukhiya hill forest from 2014 to 2020. In contrast, the average AGB content in Nijhum Dwip mangrove forest decreased from 44.36 $Mg.h^{-1}$ in 2014 to 37.46 $Mg.h^{-1}$ in 2020. The average AGB of the Madhupur deciduous forest also decreased from 110.01 $Mg.h^{-1}$ in 2014 to 107.22 $Mg.h^{-1}$ in 2020. The decreased biomass contents could be attributed to anthropogenic factors as indicated by the presence of human activities and this information will be helpful for forest restoration and management in Bangladesh.

Keywords: change detection, forest biomass, GIS

INTRODUCTION

To achieve the International Panel of Climate Change (IPCC) 1.5ºC goal, 730 billion tonnes of CO_2 (730 Pg of CO_2 or 199 Pg of C) must be removed from the atmosphere by 2100. Currently, forests absorb about 7.6 billion tons of CO_2 per year (Harris and Gibbs 2021), and some projections indicate that they could sequester around 36.7 billion tons in 2100 (Masson-Delmotte *et al.* 2022). Global forests store about 60% (~ 862 gigatons) of total terrestrial carbon and sequester close to 80% of all terrestrial aboveground and 40% below-ground organic carbon respectively. However, forest degradation, largely due to anthropogenic activities and climate change, results in CO_2 emissions of about 12 to 20% of global greenhouse gases (Pan *et al.* 2011).

Bangladesh is one of the Asian countries with a high deforestation rate (~2,600 ha annually), largely due to human activities (Macdicken *et al.* 2015). With climate change impacts affecting the weather conditions in Bangladesh, forest degradation has been exacerbated including the alteration of forest composition, structure, and biophysical processes (Littell *et al.* 2010). The combination of climate change and human actions is contributing to deforestation (Deb *et al.* 2018).

The forests of Bangladesh are categorized into four subcategories based on their geographic conditions: Swamp Forests, Mangrove Forests, Plain Land Sal Forests, and Hill Forests (Akhter *et al.* 2013). As per the Bangladesh Forest Department (BFD 2020), forests account for 12.8% of the total land area and are classified into ten classes based on the terrain, climate, location, and management principles including Bamboo Forest, Rubber Plantation, Hill Forest, Mangrove Forest, Mangrove Plantation, Forest Plantation, Shrubs with scattered tree, Swamp Forest and Swamp Plantation. Bangladesh has 2.6 million hectares of forest cover, of which about 50% is

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in rural settlements and holds 66% of the country's aboveground forest biomass. As a result, the designated forests only total 1.6 million hectares when excluding unclassified state forests and village forests (Table 1). According to BFD (2020) estimation, total carbon (C) stock on land is 1275.6 million Mg C, of which 80.5% is stored in soils (0–30 cm), 15.3% in above-ground biomass, 3.6% in below-ground biomass, 0.5% in dead wood biomass, and 0.1% in litter biomass. A total of 21.5% of the carbon stock in the entire country is stored in forests, with hill and mangrove forests contributing 9.7% and 5.2% of the total stock, respectively.

Forest resource assessment and monitoring- such as the abovementioned estimates- is important for sustainable forest management, supporting the livelihoods of communities, maintenance of ecosystem services, and carbon sequestration (Angelsen 2009). However, at present there is no complete time-series study of forest biomass and carbon in Bangladesh and how these factors change over time, which is an essential first step in understanding both the current biomass and carbon stocks as well as monitoring future carbon sequestration or losses in different regions of the country. This shortcoming is attributed to limited resources to conduct a conventional forest inventory, which is time-consuming and expensive (Unni 1983).

Recent forest inventory techniques employ digital technology, such as remote sensing and GIS, which can provide quality, quantity, and distribution data for assessment and monitoring. These techniques have been used in spatial decision support systems for forest land classification and planning, modelling, conservation, stand density, timber harvesting, (Köhl *et al.* 2006) and for identification of endangered plant species, faunal habitat zoning, detecting tree damage, mortality, insect infestation, and change (Mukul *et al.* 2014). These methods measure both qualitative (e.g., types) and quantitative (height, basal area, woody biomass, etc.) forest characteristics with ~75% accuracy (Ali *et al.* 2015).

Table 1 Forest types and their characteristics in Bangladesh (BFD 2020; Khan and Millate-e-Mustafa 2001; Rahman 2021)

Forest Type	**Description**
Hill Forests	Hill forests of Bangladesh (0.67 million ha) are mostly mixed-evergreen forests situated in the southeast (Chittagong Hill Tracts) and northeast (Sylhet Hill Tracts) (Mukul *et al.* 2016). The dominant species include *Dipterocarpus turbinatu, Swintonia floribunda*, *Lophopetalum fimbriatum*, *Duabunga sonnerationides, Salmalia insignis*, *Syzygium grande* (Reza and Hasan 2019).
Plain land Sal Forests	Plain land Sal Forests, also known as Sal moist forest (0.12 million ha) is mainly located in central Bangladesh and dominated by *Shorea robusta* with *Phyllanthus emblica, Terminalia chebula, T. Belerica*, *Careya arborea*, etc. (Chowdhury and Koike 2010).
Natural Mangrove Forests	The Sundarbans mangrove forest (0.6 million ha) is the single largest productive natural mangrove forest in the world and is in the southern coastal regions. It contains dense evergreen species dominated by *Heritiera fomes*, *Avicennia officinalis*, *A. Alba*, *Hibiscus tiliaceus*, *Excoecaria agallocha*, etc. (Reza and Hasan 2019).
Coastal Plantation Forests	Afforestation along the long shoreline was started to maintain and safeguard coastal ecosystems which currently cover an area of 0.11 million hectares. Many different types of mangrove species are planted, including *Sonneratia apetala, Avicennia officinalis, A. Marina, A. Alba, Amoora cucullata, Bruguiera sexangula, Excoecaria agallocha, Xylocarpus mekongensis, Heritiera fomes, Ceriops decandra, and Nypa fruticans* (Chowdhury *et al.* 2020; Islam *et al.* 2021).
Un-classified State Forests	This is a 0.73 million hectares area in the Chittagong Hill Tract and is managed by district councils. Major species include *Bambusa balcooa, B. Burmanica, Thyrsostachys oliveri, Melocanna baccifera, Hevea brasiliensis,* etc.
Swamp Forests and Swamp Plantation	Covers 0.02 million hectares and is mostly found in the north-eastern region (Sylhet and Sunamganj district). Major species include Hijol or Indian oak (*Barringtonia acutangular*), Koroch (*Pongamia pinnata*), Pitali (*Trewia nudiflora*), and Borun (*Crataeva magna*) (Sohel *et al.* 2023).
Privately Owned Village Forests and Forest Plantation	Also known as homestead forests, span 0.27 million hectares and are dispersed throughout the county.

Bangladesh conducted its first national forest resource assessment in 2007 (Altrell *et al.* 2007), however, there is little information available on earlier data-collecting techniques and there are inconsistencies in methodology, and data-sharing arrangements (Costello *et al.* 2016). In response to the growing need for data on trees and forest resources, a second, more thorough institutionalized forest inventory was released in 2020. It was based on remote sensing and included biophysical, land-use, and socioeconomic data (Henry *et al.* 2021). In Bangladesh, forestry information is still highly valued and is included in significant national plans, strategies, and policies due to the severe burden that energy and food production places on the country's forests (BFD 2020). As a result, inventories of forest resources are important for managing Bangladesh's endangered forests sustainably.

This study's objective is to estimate the change in forest aboveground biomass between 2014 and 2020 in four forest zones (Mangrove Forest, Hill Forest, Sal Forest, and Coastal Plantation Forest) in five districts of Bangladesh (Table 2) using Landsat 8 imagery data. The main purpose is to understand the change in total tree biomass and generate maps showing changes in aboveground biomass.

MATERIALS AND METHODS

Study Location

This study focused on four designated forests in Bangladesh that provide socioeconomic and ecological benefits but are also deteriorating and losing forest cover because of human pressures and natural disasters (Figure 1).

The Sundarbans Mangrove Forest covers 927,700 hectares and is the biggest continuous stretch of mangroves in Bangladesh. They are highly productive, have a rich floral and faunal diversity, and have a significant impact on the national and regional economies and climate (Mahmood *et al.* 2021). A million people rely on the Sundarbans for their livelihoods, and the area offers numerous direct benefits like fuelwood collection, fishing, and protection from tropical cyclones and tidal surges for their lives and property (Aziz and Paul 2015). It also manages coastal and riverbank erosion, aids in the sequestration and storage of carbon, and supports soil nutrient cycling (Hale *et al.* 2019; 2015). Bangladesh has over 60% of the Sundarbans, which make up 4.13% of the country's total landmass and 38.12% of its total forest area (BFD 2017). However, the Sundarbans are under threat from both natural and man-made sources, including erosion, tropical cyclones, salinity intrusion, and sea level rise, as well as from human settlement, overfishing, industrial development, pollution, and tourism (Giri *et al.* 2011; Uddin *et al.* 2019). Consequently, from the 1990s to the 2000s, there was a net loss of 1.1% (10000 ha) of Bangladesh's Sundarbans; hence, it is critical to continuously monitor the Sundarbans' forest cover to maintain this global heritage (Giri *et al.* 2015).

Madhupur Sal Forest is a Plainland Sal Forest, one of the most abundant and ecologically appealing forest types (Islam *et al.* 2023) but it has been severely damaged by agriculture and other human activities (Rahman *et al.* 2009). Around 7,079.4 hectares of Sal Forest were destroyed between 1972 and 2013 as a result of the quick destruction and severe disruptions caused by both local and indigenous inhabitants (Al Faruq *et al.* 2016). The Madhupur Sal Forest is surrounded by densely populated areas, which puts pressure on the forest's resources and accelerates their degradation (Rahman *et al.* 2009). The main causes of forest degradation are encroachment, illegal tree merchants, shifting cultivation, ethnic people's energy and wood consumption, and the introduction of exotic species (Yasmin *et al.* 2010).

The Ukhiya Hill Forest, Whykhing, and Teknaf forest ranges make up Cox's Bazar Forest Lands, which enclose 21,848 hectares of the Chittagong Hill Forest (Nur *et al.* 2016). Tropical evergreen and semi-evergreen vegetation, which makes up this forest, is very important for the variety of flora and fauna and for sustaining the livelihood of the local population. However, the majority of Bangladesh's deforestation took place in this forest area because of population settlement, shifting agriculture, and illicit logging (Reddy *et al.* 2016; Salam *et al.* 1999). Since 1991, over 931,447 Rohingya refugees have migrated to Bangladesh (UNHCR 2023); the bulk of them are now living in camps built by indiscriminately removing 1,747.45 ha of natural vegetation and leveling hills in the upazilas of Teknaf and Ukhiya in the Cox's Bazar district (Hossain and Haider 2020; Sarkar *et al.* 2023). As a result, it caused changes to the environment, including topsoil loss that resulted in unproductive land, erosion, a potential risk of landslides, and a threat to the biodiversity of the local and regional areas (Mahmood *et al.* 2021). Hasan *et al.* (2021) showed that in 2016, Ukhia's forest area had fallen by 82% because of severe deforestation. Therefore, effective change detection and analysis through appropriate monitoring are essential for the conversion of this protected area and sustainable management (Akhtar *et al.* 2022; Hossain and Moniruzzaman 2021).

The Nijhum Dwip Forest is a Coastal Plantation Forest that is a distinctive mangrove ecosystem and unique wildlife habitat for the native spotted deer population (*Axis axis*), and a wintering site for a significant number of migratory water birds, including several endangered species (Nishorgo Network 2018). Natural disasters like cyclones and tidal erosion, as well as human activities like unlawful harvesting and turning forest areas into agricultural land, have caused a loss of over 42% of forest area from 1990 to 2020 (Islam *et al.* 2021). To preserve and sustainably manage this protected area, the Government of Bangladesh (GoB) designated 16,350 hectares of Nijhum Dwip as a national protected area in 2001 (Hossain *et al.* 2016).

Table 2 Study area and forest types included in this forest biomass assessment.

BFD Class (BFD 2020)	**Study area**	**Study locations**	**Area covered (ha)**
Hill Forests	Ukhiya Hill Forests	District: Cox's Bazar Upazila: Ukhia(21°16'59.88" N and 92°05'60.00" E)	26,180
Coastal Plantation Forests	Nijhum Dwip	District: Noakhali Upazila: Hatiya(22° 05' 35" N and 91° 00'13.7" E)	16,352
Plain land Sal Forests	Madhupur Sal Forest	Distract: Tangail Upazila: Madhupur(24°37'0.12" N and 90°01'30.00"E)	36,692
Natural Mangrove Forests	Sundarbans Mangrove Forest	District: Khulna Upazila: Dacope Administrative Range: Khulna Range(22°46'45" N and 89°43'49"E)	74,672
		District: Khulna Upazila: Koyra Administrative Range: Nalian Range(22°4'26.6" N and 89°24'2.6" E)	61,450
		District: Bagerhat Upazila: Sarankhola Range:(22°2'56.4" N and 89°48'10.2" E) and Management Range: Sarankhola Range Mongla(22°4'7.7" N and 89°39'17.9" E) Chandpai Range	132,495
		District: Bagerhat Upazila: Mongla Administrative Range: Chandpai Range(22°4'7.7" N and 89°39'17.9" E)	130,995

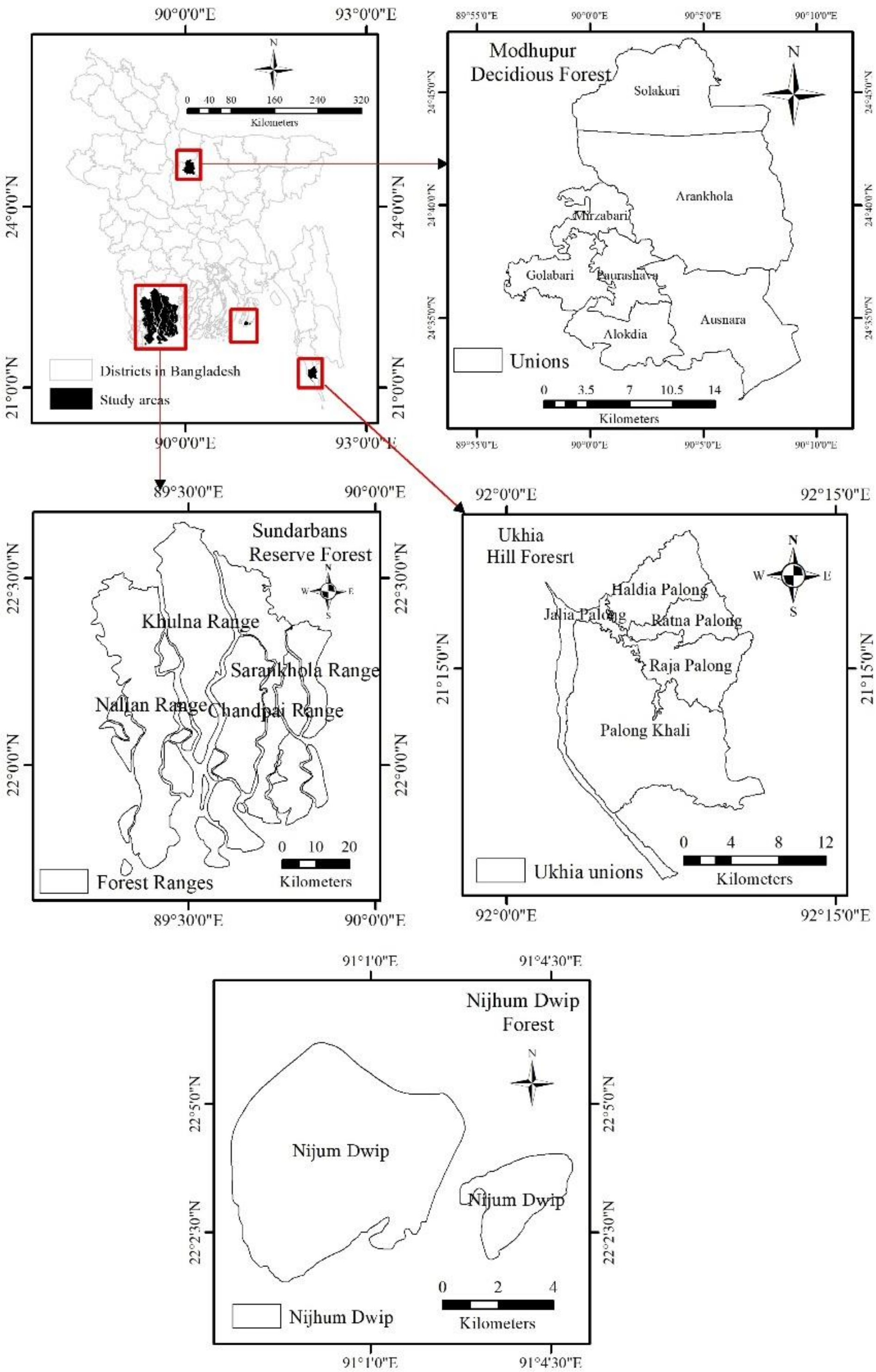

Figure 1 The country-level map shows the locations of study areas, with expanded maps for each of the regions where changes in forest biomass were assessed

Aboveground Biomass (ABG) Data Acquisition and Estimation

This study used multi-spectral Landsat-8 satellite images, with a 30 x 30 m resolution, for the years 2014 and 2020 acquired from the USGS open-source satellite database (https://earthexplorer.usgs.gov/) (Table 3). The images were processed and analyzed in ArcGIS 10.2.1.

This study followed the procedure used by Tripathi *et al.* (2010) for calculating carbon sequestration (Figure 2). The Normalized Difference Vegetation Index (NDVI) (Eq. 1) was calculated from satellite data (Tucker 1979) and used to calculate the fraction of photosynthetically active radiation (FPAR) (Hu *et al.* 2017; Sims *et al.* 2006) (Eq. 2), photosynthetically active radiation (PAR) (Sellers *et al.* 1995) (Eq. 3), and absorbed photosynthetically active radiation (APAR) (Eq. 4) (Field *et al.* 1995).

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)} \; or \; \frac{APAR}{PAR} \quad (1)$$

Again,

$$FPAR = (1.24 \times NDVI) - 0.168 \quad (2)$$

PAR is restricted to just a portion of sunlight's spectrum from 400 to 700 nanometers (nm). PAR is estimated from sunrise to sunset and is given by the formula:

$$PAR = \frac{GHI}{365} \, Wm^{-1} \quad (3)$$

Where, GHI is the Global Horizontal Irradiance (Rn), retrieved from the World Bank solar irradiance project (Suri *et al.* 2020).

APAR is the available energy in vegetation for photosynthesis that is calculated each month and the product of PAR surface irradiance and the fraction of photo-synthetically active radiation (FPAR).

$$APAR = FPAR \times PAR \quad (4)$$

According to Field (1995), biomass is the function of APAR and light use efficiency (LUE). In practice, it is impacted by environmental variables like temperature and vapor pressure deficit (VPD), which can be derived from meteorological factors (Eq. 5).

$$\varepsilon \; or \; LUE = \varepsilon^{\circ} \times T_1 \times T_2 \times W \; (g/MJ) \quad (5)$$

Where T_1 and T_2 represent the effect of high and low temperatures on LUE i.e., relate to plant growth regulation (acclimation) by temperature; W represents the effect of moisture on LUE; and ε° represents the maximum light utilization rate under ideal conditions which is globally uniform maximum 2.5 g/MJ. The T_1 denotes the depressant effect on the Net Primary Product (NPP) of high and low temperatures restricting the process of photosynthesis.

Table 3 Landsat 8 data source and resolution used to estimate aboveground biomass in four forest types in Bangladesh

Forest Type	Satellite Data	Spatial Resolution (m)	Acquisition Date
Hill Forest	Landsat-8 OLI/TIRS C2 Level 2	30×30	02.03.2014 & 02.13.2020 (Path: 136, Row: 45)
Nijhum Dwip Forest	Landsat-8 OLI/TIRS C2 Level 2	30×30	02.03.2014 & 02.04.2020 (Path: 136, Row: 45)
Madhupur Sal Forest	Landsat-8 OLI/TIRS C2 Level 2	30×30	01.25.2014 & 02.11.2020 (Path: 137, Row: 43)
Sundarbans Reserve Forest	Landsat-8 OLI/TIRS C2 Level 2	30×30	01.14.2014 & 02.13.2020 (Path: 137, Row: 45)

The plant acclimation by temperature (i.e., T_1 and T_2) and effect of moisture on LUE i.e., W which is the function of the ratio of Estimated Evapotranspiration (EET) and Potential Evapotranspiration (PET) were estimated by following (Eq. 6), (Eq. 7) and (Eq. 8) (Field *et al.* 1995; Potter *et al.* 1993).

$$T_2 = C \left|\frac{1}{1+exp^{(0.2 \times T_{OPT}-10-T_{mon})}}\right| \times \left|\frac{1}{1+exp^{(-0.3 \times T_{OPT}-10+T_{mon})}}\right| \quad (6)$$

Where:

T_{opt} = Mean temperature during the month of maximum NDVI in 2014 and 2020. Islam and Mamun (2015) found October has the maximum NDVI for Bangladesh and the mean temperature of this month was 26.4 ^{0}C in 2014 and 31.2 ^{0}C in 2020 (BMD 2020).

T_{mon} = Mean monthly air temperature in 2014 and 2020. Based on satellite image acquisition, our study used average mean air temperature for January and February as 19.41 ^{0}C for 2014 and 22.12 ^{0}C for 2020 (BMD 2020).

C = constant = 1.185

And,

$$T_1 = 0.8 + 0.02 \times T_{opt} - 0.0005 \times (T_{opt})^2 \quad (7)$$

$$W = 0.5 + \frac{EET}{PET} \quad (8)$$

PET is the function of temperature and latitude while EET is the function of precipitation (P) and net solar irradiance (Rn), which is being converted to the equivalent evaporation through specific heat of water Field *et al.* (1995). When EET exceeds PET, NPP is no longer restricted by water. This study used a coefficient value of 0.85 for water scaler (W) from a study in Bangladesh (Islam and Alam 2021). Therefore, the amount of biomass was estimated from the ratio amount of APAR and PAR (or NDVI) multiplied by LUE that helps plant biomass increment (Eq. 9).

$$Biomass = APAR \times LUE\ (g/m^2) \quad (9)$$

The amount of biomass content per m^2 was estimated based on the number of pixels of clusters of Landsat-8 OLI/TIRS C2 Level 2, 30 m sensor multiplied by the squared resolution of the image. The estimated biomass was converted to megagrams per hectare ($Mg.ha^{-1}$), divided into four groups, and then mapped using the "natural break" method.

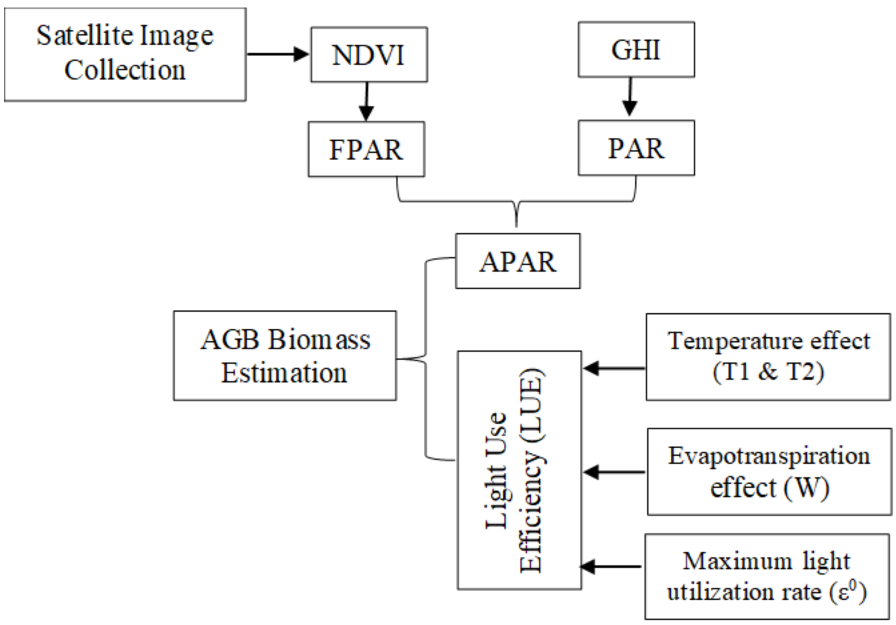

Figure 2 Simplified workflow of satellite-based aboveground forest biomass estimation

RESULTS AND DISCUSSION

The average AGB content per hectare in Sundarbans Reserve Forest slightly increased from 89.73 $Mg.ha^{-1}$ in 2014 to 90.76 $Mg.ha^{-1}$ in 2020 (Table 4), but the changes varied across the forest. The maximum AGB content increased (4%) at Sharankhola Range from 98.13 $Mg.ha^{-1}$ to 102.36 $Mg.ha^{-1}$ and decreased (2%) at Chandpai Range from 81.76 $Mg.ha^{-1}$ in 2014 to 80.0 $Mg.ha^{-1}$ in 2020 respectively (Figure 3a and Figure 3b). According to Global Forest Watch (GFW 2022), Bagerhat and Khulna lost 0.05% of tree cover during 2000-2021 which resulted in 64.9 MT CO_2 and 13.9 MT CO_2 emissions respectively. Sundarbans Reserve Forest is under pressure due to the high dependency of local poor communities on its natural resources for their survival and livelihoods and the current unsustainable management practices (Mahmood *et al.* 2021). One step to address this was conducted by the Forest Department and other partners by planting around 290,000 ha of coastal mangrove forests by involving local stakeholders via a co-management method (SER 2022).

In contrast, the Madhupur Sal Forest in Tangail district lost around 14,000 ha (9.1%) of tree cover from 2001 to 2021 which released 555 MT of CO_2 emissions to the atmosphere (GFW 2022). The average AGB content per hectare in Madhupur Sal Forest has decreased from 110.01 $Mg.ha^{-1}$ in 2014 to 107.22 $Mg.ha^{-1}$ in 2020 respectively but changes also varied across this area. The maximum AGB content increased (16%) at Golabari from 118.54 $Mg.ha^{-1}$ to 137.66 $Mg.ha^{-1}$ and decreased at Mirzabari union (14%) from 111.24 $Mg.ha^{-1}$ in 2014 to 95.35 $Mg.ha^{-1}$ in 2020 respectively (Figure 4a and Figure 4b). Illegal felling and settlement, grazing, encroachment, industrial and agricultural expansions, agroforestry (banana, pineapple, garlic, zinger, etc.), and firing range practice by the military are found as the underlying causes of deforestation in Madhupur Sal Forest (Mollick *et al.* 2018; Rahman *et al.* 2009). Cox's Bazar lost around 9,600 ha (22%) of its forest cover during the last two decades (2000-2021) resulting in 4.6 MT CO_2 emissions (GFW 2022).

Similar to the Madhupur Sal Forest, the average per hectare AGB content in the Ukhia hill forest also decreased. The maximum AGB content in Jalia Palong union increased approximately doubled from 4.08 $Mg.ha^{-1}$ to 8.17 $Mg.ha^{-1}$ but the biomass density numbers remain low in this area. The biomass in the rest of this region remained the same or increased slightly from 2014 to 2020 (Figure 5a and Figure 5b). Ullah *et al.* (2022) identified overpopulation, agricultural and industrial extensions, poverty, unemployment, and illegal logging as the proximate drivers of deforestation in the Teknaf area. Activities contributing to these changes include excessive timber and fuelwood extraction, infrastructure extension, agricultural expansion, encroachment, and betel leaf cultivation (Rashid 2017). Meanwhile, the influx of Rohingya refugees from Myanmar since 2017 resulted in the loss of 3,238 ha. This influx induced deforestation in Ukhiya, The Forest Department (FD) and non-governmental organizations restored 2,600 ha area along with 600 ha replanted by Rohingya people by 2018 (Khan 2022). Even though afforestation programs are being initiated to restore these areas, coastal forests are still threatened by land erosion, illegal harvesting of plant resources, tropical natural calamities as well, and conversion of forest land into agricultural land (Chowdhury *et al.* 2020; Islam *et al.* 2021). Noakhali lost 322 ha of tree cover from 2000 to 2021 which led to emissions of 52.5 MT CO_2 in the atmosphere (GFW 2022). Nijhum Dwip Forest also lost average AGB per hectare (16%) from 44.36 $Mg.ha^{-1}$ in 2014 to 37.46 $Mg.ha^{-1}$ in 2020 (Figure 6a and Figure 6b).

Table 4 Aboveground biomass content in 2014 and 2020 in four different forest types (in parentheses below forest name) and the associated areas of the forest of Bangladesh

Forest type and union names	2014 ($Mg.ha^{-1}$)	2020 ($Mg.ha^{-1}$)
Sundarban Mangrove Forest (Natural Mangrove)		
Khulna Range	84.37	84.90
Sharankhola Range	98.12	102.36
Nalian Range	94.64	95.78
Chandpai Range	81.76	80.00
Average	*89.73*	*90.76*
Madhupur Sal Forest (Plain Land Sal Forest)		
Alokdia	99.87	99.87
Solakuri	108.58	102.75
Ausnara	108.88	100.29
Golabari	118.54	137.66
Mirzabari	111.24	95.35
Madhupur Paurashava	114.46	114.46
Arankhola	108.53	100.18
Average	*110.01*	*107.22*
Ukhia Hill Forest (Hill Forest)		
Jalia Palong	4.08	8.17
Palong Khali	3.03	3.25
Raja Palong	10.42	10.93
Ratna Palong	11.13	11.13
Haldia Palong	10.77	10.77
Average	*7.89*	*8.85*
Nijhum Dwip Forest (Mangrove Plantation)	44.36	37.46

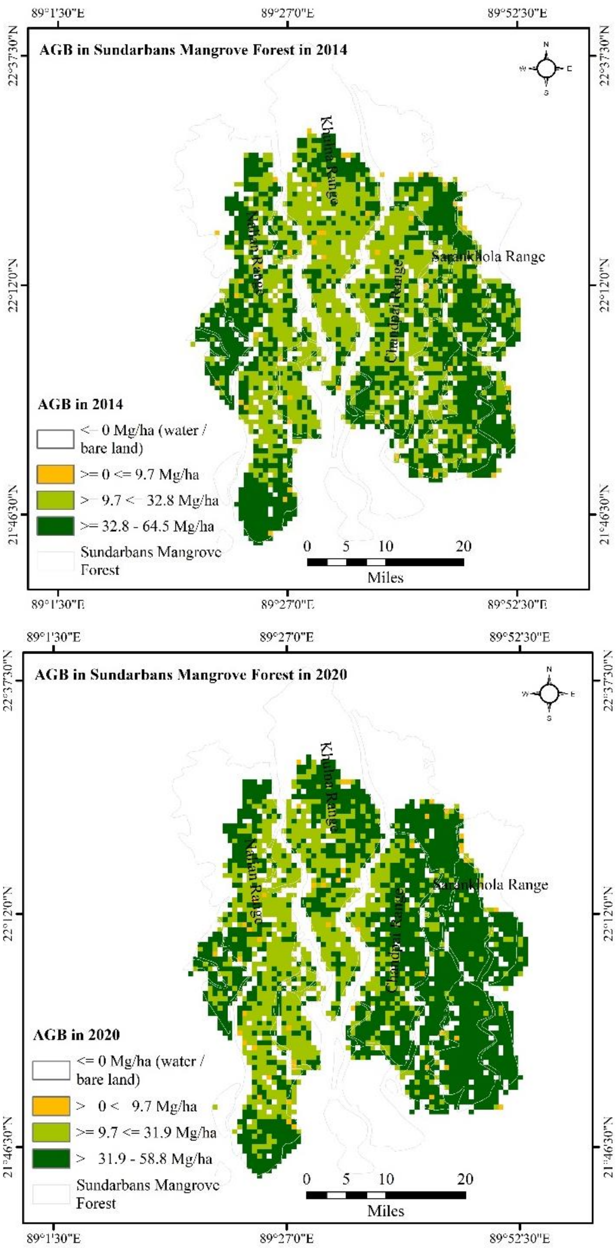

Figure 3 Spatial distribution of biomass (Mg.ha^{-1}) in the Sundarbans Mangrove Forest (a) 2014 (b) 2020. Each pixel represents a 30 x 30 m area

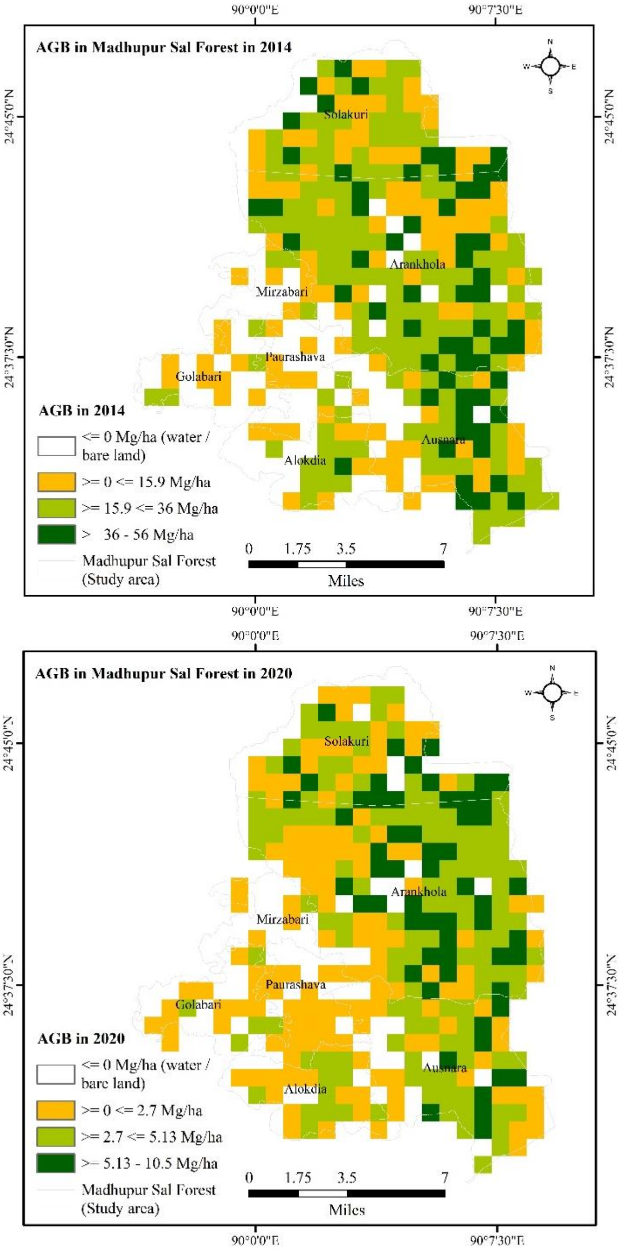

Figure 4 Spatial distribution of biomass (Mg.ha^{-1}) in Madhapur Sal Forest (a) 2014 (b) 2020

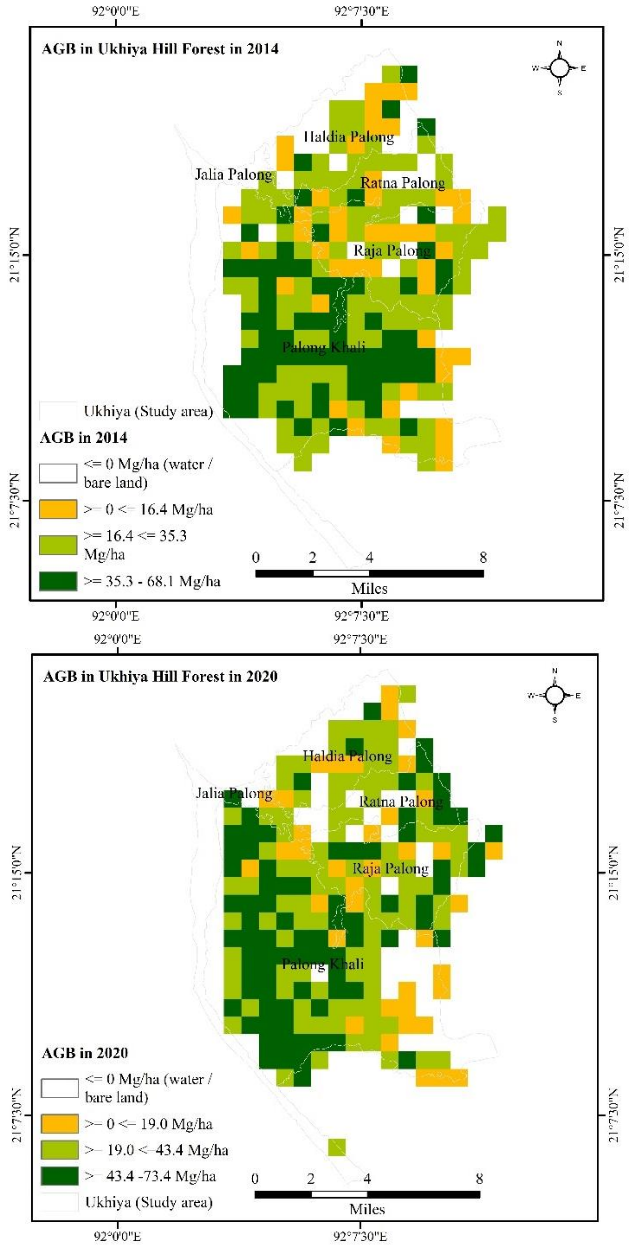

Figure 5 Spatial distribution of biomass ($Mg.ha^{-1}$) in Ukhia Hill Forest (a) 2014 (b) 2020

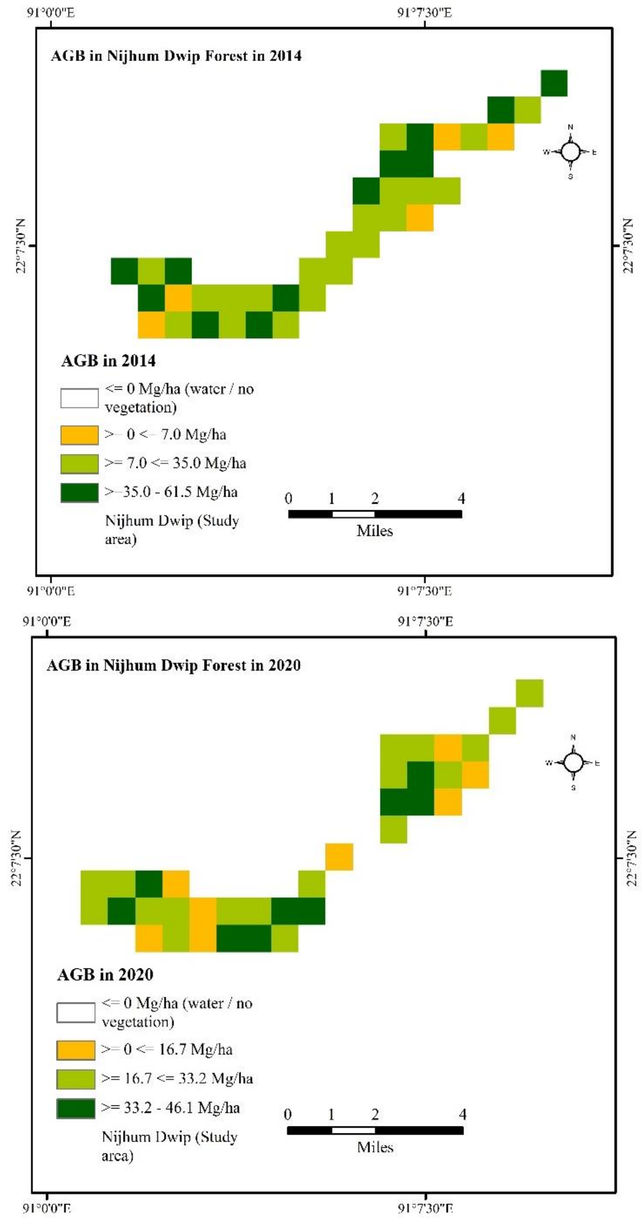

Figure 6 Spatial distribution of biomass (Mg.ha^{-1}) in Nijhum Dwip Forest (a) 2014 (b) 2020

In the four forests assessed in this study, the estimated average AGB in 2014 was about 63 Mg.ha^{-1} (minimum 3.03 Mg.ha^{-1} to maximum 118.54 Mg.ha^{-1}) and it dropped to 61 Mg.ha^{-1} (minimum 3.25 Mg.ha^{-1} to maximum 137.7 Mg.ha^{-1}) in 2020. The average minimum AGB stock was observed in the hill forest with estimated values of 7.89 Mg.ha^{-1} and 8.85 Mg.ha^{-1} while the average maximum stock reported was 110.01 Mg.ha^{-1} and 107.22 Mg.ha^{-1} during both years of estimation.

The average AGB stock in the forests of Bangladesh was 63 Mg.ha^{-1} in 2014 and 61 Mg.ha^{-1} in 2020, which are lower than other reported values of 145.47 Mg.ha^{-1} (BFD 2020), 159.5 to 360 Mg ha^{-1} (Rahman *et al.* 2015), 49 to 121 Mg.ha^{-1} (Alamgir and Turton 2013), 158 Mg.ha^{-1} (Brown *et al.* 2001), 93 Mg.ha^{-1} (Eggleston *et al.* 2006), 92 Mg.ha^{-1} (Brown 1997), 137 Mg.h^{-1} (DeFries *et al.* 2002), and 175.5 Mg.ha^{-1} (Mukul *et al.* 2014). However, the estimation is very close to a satellite-based study conducted by Saatchi *et al.* (2011), which reported a value was 70.5 Mg.ha^{-1}. Other inventory or harvest data-based studies observed similar values like Gibbs *et al.* (2007) reported 65 Mg ha^{-1}, 55 Mg.ha^{-1} by FAO (2010), and 62 Mg.ha^{-1} by Rahman (2021) (Table 5). In addition to differences in methods used for these assessments, this study only examined four representative forests in Bangladesh so does not capture the forest biomass across all the forested land in the country.

Table 5 Biomass estimations and methods for Bangladesh from different studies

Study	Study type	Biomass stock (Mg.ha^{-1})
Present study	Satellite (2014 image)	63
Present study	Satellite (2020 image)	61
BFD (2020)	Inventory	145.47
Rahman *et al.* (2015)	Inventory	159.5–360
FAO (2010)	Inventory	55
Alamgir and Turton (2013)	Inventory	49-121
Saatchi *et al.* (2011)	Satellite	70.5
Brown *et al.* (2001)	Harvest data	158
Rahman (2021)	Inventory	62
Gibbs *et al.* (2007)	Harvest data	65
Eggleston *et al.* (2006)	Harvest data	93
Brown (1997)	Inventory	92
DeFries *et al.* (2002)	Harvest data	137
Mukul *et al.* (2014)	Literature based modeling	175.5

This study found a low amount of biomass stock in the hill forests of Bangladesh compared with 115.6 Mg.ha^{-1} and 103.4 Mg.ha^{-1} reported values by Ullah and Al-Amin (2012) and Mukul *et al.* (2016). A huge variation in AGB stock in Madhupur Sal Forest compared with 153.9 Mg.ha^{-1} and 34.5 Mg.ha^{-1} was estimated by Kibria and Saha (2011) and Mukul *et al.* (2014). However, the AGB stock for Sundarbans Mangrove Forest reported values by Mukul *et al.* (2014) and Rahman (2021) as 88.2 Mg.ha^{-1} and 98.9 Mg.ha^{-1} which are very close to the present study. Similarly, the estimated biomass value of Nijhum Dwip Forest is also very close to the 19.6 Mg.ha^{-1} reported value by Mukul *et al.* (2014) (Table 6). The variations might be due to differences in methods, areas studied like north-eastern versus south-eastern hill forest areas, as well as month and year of satellite data acquisition. For example, NDVI concentration remains similar in a season (Tripathi *et al.* 2010) but changes between months with the lowest values in February and the highest in October (Islam and Mamun 2015). This study used satellite images for January and February i.e., the winter season, which might contribute to the lower estimation. Moreover, higher spatial resolution, such as that used in this study (30 m × 30 m), has limitations, such as the potential inability to estimate finer changes over time, the incapability to estimate biomass under dense canopies (Lu *et al.* 2012), variation in estimation due to sensor angles in challenging terrain with steep slopes, and the potential to be affected by moisture content variation of the surrounding atmosphere. The accuracy of these results can be increased in future studies by adding other data sources, such as extended band SAR, LiDAR, high spatial resolution, and auxiliary data for AGB estimates (Li *et al.* 2020).

Table 6 Aboveground biomass in different forest types of Bangladesh

Study	Hill Forest (Mg.ha^{-1})	Sundarbans Mangrove Forest (Mg.ha^{-1})	Madhupur Sal Forest (Mg.ha^{-1})	Nijhum Dwip Forest (Mg.ha^{-1})
Mukul *et al.* (2014 a)	49. 5	88.2	34.5	19. 6
Mukul *et al.* (2014 b)	103.4	-	-	-
Ullah and Al-Amin (2012)	115.6	-	-	-
Alamgir and Al-Amin (2007)	73.6	-	-	-
Shin *et al.* (2007)	92.0	-	-	-
Rahman *et al.* (2015)	-	98.9	-	-
Donato *et al.* (2011)	-	126.7	-	-
Kibria and Saha (2011)	-	-	153.9	-
BFD (2020)	24.03	49.28	31.36	21.79
Present study, 2020	8.85	90.76	107.22	37.46
Present study, 2014	7.89	89.73	110.01	44.36

CONCLUSION

This satellite-based study found considerable variation in the aboveground biomass among the four different forest types of Bangladesh. It showed that average AGB stock increased in Sundarbans Reserve Forrest and Ukhiya Hill Forest while decreasing in Nijhum Dwip Forest and Madhupur Sal Forest. Bangladesh has set a target to stop forest losses and increase forest cover from 22.37% to 24%, reforest 150,000 ha of coastal areas, and restore 137,800 ha of destroyed and 200,000 ha of degraded hill and Sal Forest by 2030 (MoEFCC 2021). This study helps to identify areas under human pressure and could be used to identify priority areas for action.

This study had a lower estimate of AGB than some other studies (e.g., 159.5 to 360 $Mg.ha^{-1}$ by Rahman *et al.* (2015)). These studies' estimates were very close to studies with similar inventory or harvest data-based methods (e.g., Saatchi *et al.* (2011)) but there was wide variation with other methods. Better agreement between methods and an improvement in data quality can be enhanced by the replication of the study and including ground truthing in the study areas, especially for the dominant species like *Nypa fruticans* for Sundarbans Reserve and Nijhum Dwip Forest or *Shorea robusta* for Madhupr Sal Forest. Bangladesh needs an accurate national level assessment of forests using both satellite and inventory based methods that can be used to improve forest management and aforestation planning to achieve nationally determined contribution (NDC) goals by 2030.

Our research will be useful in determining how the AGB biomass of forests under human pressure has changed over time. The results may be used to compare the change, which will help to determine the root reasons for the AGB change. Identifying these areas and the associated causes of the change can guide the organizations and agencies who are involved in protecting and managing these areas to develop targeted plans to reduce forest loss in the future.

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