Estimation and Modelling of Above Ground Biomass of Mangrove Forest in Keti Bunder, Indus Delta

By

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DEDICATION

To

Almighty Allah

&

My dearest parents, my loving husband, and our precious baby

Your encouragement, sacrifices, tireless belief, patience, and unwavering support is the sole reason I am where I am today. This accomplishment is the testament of the remarkable family Allah has blessed me with. This thesis is the evidence of my profound gratitude.

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To my husband, you have been my rock of unwavering support. I am forever grateful for your patience and encouragement.

To my little one, you inspire me to continue striving for the better and provide you with the best possible future.

Areeba Binte Imran

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
AGB	Above Ground Biomass
BGB	Below Ground Biomass
AGC	Above Ground Carbon
BGC	Below Ground Carbon
BCE	Blue Carbon Ecosystems
GPS	Global Positioning System
SPSS	Statistical Package for Social Sciences
TOA	Top-of-Atmosphere
BOA	Bottom-of-Atmosphere
Dbh	Diameter at Breast Height
MSI	Multi Spectral Instrument
SD	Standard Deviation
r	Pearson's correlation coefficient
r^2	Coefficient of determination
RMSE	Root Mean Square Error
Sig.	Significance

ABSTRACT

Mangroves forest ecosystem, distributed along the coastal belts of Pakistan, are in a constant flux. They play a key role in carbon cycle and support biodiversity. Accurate mangrove forest Above Ground Biomass (AGB) estimation is an integral part of sustainable forest management and help to understand how they are affected by climatic changes and anthropogenic activities. The current study's aim was to construct a non-destructive allometric equation derived by performing stepwise linear regression on field AGB and vegetation indices to estimate the AGB of mangroves of Keti Bunder. The objectives of the current study were (a) analyze the correlation between field AGB and selected vegetation indices, (b) develop a regression equation based on stepwise linear regression, (c) estimate the amount of carbon stock and CO_2 sequestered by the study area. 30 sample plots and 5 vegetation indices were used to analyze the potential of Sentinel-2 to predict AGB. It was found that Modified Simple Ratio (MSR) exhibit strong correlation with field AGB (r = 0.73, r^2 = 0.54) as compared to GNDVI, NDVI, CMRI and NDI45. The estimated AGB of the study area from the predicted model was found to be up to 51 t/ha (r^2 = 0.643). The Root Mean Square Error (RMSE) value was 16.6 t/ha. It was concluded that vegetation indices derived from Sentinel-2 can demonstrate good results in AGB prediction for mangrove forests.

Chapter 1

INTRODUCTION

1.1. Background

Mangrove ecosystems are the only woody halophytes found near the tropic and subtropical coastlines, linking terrestrial and marine systems (Alongi, 2002). Spanning over 181,000 km^2 of coastlines, mangroves have high ecological and economical value. They act as nursery and breeding sites for various species, source of fuel, Non-Wood Forest Products (NWFP), stabilize shorelines and protect against natural hazards like waves, tsunami, erosion (Alongi, 2002). Increase in human population has led to unrestricted clear cutting, aquaculture, land conversion and pollution causing the destruction of mangroves ecosystem (Lee et al., 2014).

Mangroves, also known as the Blue Carbon Ecosystems (BCE), covers about 0.2% of the world's coastlines and are major long term burial sites of carbon (Chatting et al., 2022). Mangroves can store and sequester up to five times more carbon than the terrestrial forest ecosystems (Donato et al., 2011) owing to their high productivity and soil decomposition rates (Alongi, 2012). Furthermore, their complex root structure and reproduction, combined with waterlogged soil, trap allochthonous organic material on top of peat (preserved remains of partially decomposed and disintegrated plant material due to waterlogging, oxygen deficiency and high acidity) up to a depth of 10 meters (McKee, Cahoon & Feller, 2007). As a result, mangroves have garnered a great deal of interest from the scientific community.

These highly productive forests have undergone a steep decline because of high demand for human commodities leading to over exploitation of aquaculture, felling and land conversion (Richards & Friess, 2016). Goldberg and his fellows (2020) estimated a significant loss of 62% globally between 2000 and 2016 in Southeast Asia due to land conversion to aquaculture and agriculture. Consequently, an estimate of > 300 million Mg of CO_2 was emitted between 2000 and 2012 (Hamilton & Friess, 2018). Such drastic release of stored carbon has a direct impact on greenhouse gas (GHG) emission which is the major factor contributing towards climate change (Chatting et al., 2022). Therefore, conservation and restoration programs on national and international level are essential (Cameron, Hutley, Friess & Brown, 2015). Rise in sea level, water inundation period and duration has been identified as the most significant factors of climate change to effect mangrove mortality rate (Ward, Friess, Day & Mackenzie 2016; Lovelock and Reef, 2020).

To prevent this, quantitative information about the carbon dynamics of mangroves is needed. Widely used approach for mangrove forest inventory is through field survey, which is time consuming, expensive, laborious, destructive, and sometimes erroneous due to muddy soil conditions and heavy weight of wood. This limitation requires accurate, reliable, and timely information of the distribution and dynamics of mangrove forests.

With the recent advancement in the remotely sensed data, its preprocessing, computing, availability, expertise in handling and applicability has generated a flux of studies solely based on mangroves. This has led to the formation of novel techniques in Above Ground Biomass (AGB) calculation considered essential for resource planning, management, decision making and reporting to international treaties and conventions, among other aspects.

Pakistan, regardless of this advancement, neither has reliable, accurate and timely information on the ever-changing mangroves forests, nor any study has been conducted for its biomass calculation through remote sensing. Pakistan is a signatory of the Kyoto Protocol, making it necessary to report its biomass and carbon stock at regional and national level (Khan, Khan, Ali & Nazre, 2021). This study aims to offer a baseline to monitor regional and national trends in mangroves carbon stocks.

1.2. Literature Review

Compared to the traditional method of destructive (tree felling) and non-destructive approach (allometric equations) of biomass calculation, remote sensing techniques provide rapid, continuous global coverage. Mangroves, despite having spatial constraints for data collection, have a distinct spectral signature in the visible red, near infrared and mid infrared range, making it easier to separate from other land cover types (Giri., 2021; Baloloy, Blanco, Sharma & Nadaoka 2018). Numerous studies have incorporated remotely sensed data with field sample plots data for AGB estimation.

Over the years, researchers have proposed a myriad of techniques of AGB estimation. Extensive review was carried out to identify best remotely sensed data in terms of efficiency, performance, and ease of use. Remotely sensed data has its own constraints, for example image and processing cost, data volume, redundancy in data and storage. Li and his colleagues incorporated filed data and sentinel-2 imagery to construct urban forest biomass estimation models for the city of Xuzhou. They found that stepwise regression models yield better estimates than multiple regression models estimations (RMSE = 7.99 t/hm^2, 45.66 t/hm^2 and 6.89 t/hm^2 for low vegetation, for broadleaved forest, and for coniferous forest respectively) (Li et al., 2020).

Many comparative studies have been carried out to deduce the biomass prediction potential of various satellites in terms of efficiency, accuracy, and cost effectiveness. A study compared sentinel-2, RapidEye and PlanetScope imagery and deduced sentinel-2, despite being freely available, generated a higher coefficient of determination i.e., $r^2 = 0.89$ when multispectral bands were used as predictors of above ground biomass (AGB) (Baloloy et al., 2018). In a study conducted in 2018, 24 different sentinel-2 vegetation indices were compared for accessing mangrove density. The researchers found that NDVI and RVI (Ratio Vegetation Index) with exponential approach and NDVI with polynomial approach gave the highest accuracy (Muhsoni, Sambah, Mahmudi, & Wiadnya, 2018). In another study, a regression equation for the estimation of AGB was developed using field AGB and NDVI. The study concluded that the biomass of the mangroves of Kerala ranged from 878 gm per pixel to 44226 gm per pixel where as the carbon content ranged from 417 gm to 21007 gm per pixel (Bindu, Rajan, Jishnu, & Ajith Joseph, 2020). Wicaksono et al. mapped the carbon stock of the mangroves of Karimunjawa Islands utilizing Advanced Land Observing Satellite (ALOS) Advanced Visible and Near Infrared Radiometer (AVNIR) PC (Principal Component) bands. Their result showed a maximum accuracy of 77.8% and 60.8% for Above Ground Carbon (AGC) and Below Ground Carbon (BGC) (Wicaksono et al., 2016). Similarly, Castillo et al., evaluated the ability of Sentinel-2 for the prediction of AGB of mangroves using machine learning algorithms. They found that model constructed using Leaf Area Index (LAI) was more accurate in predicting AGB (Castillo, Apan, Maraseni, & Salmo, 2017)

Normalized Difference Vegetation Index (NDVI) is seen to be widely used for above ground biomass estimation due to high reflectance of near infrared region (NIR) (Huang, Deng, Zhang, & Wan, 2016). However, NDVI saturates areas of dense vegetation, over predicting its biomass (Askar et al., 2018). Utilization of the red edge band in vegetation indices greatly reduces this problem (Mutanga & Skidmore, 2004). In a study conducted on mangroves in 2015 also concluded that species information and indices derives from the red edge band are more sensitive to mangrove biomass estimation (Zhu et al., 2015).

Sentinel-2, launched by the European space agency (ESA) on 23rd June 2015, is a multispectral constellation of two identical polar orbiting satellites with a swath width of 290 km. It has 13 bands with 3 spatial resolutions (i.e., 10 m, 20 m, and 60 m), 12-bit radiometric resolution with a revisit time of 5 days (ESA).

1.3. Purpose of the Study

In the past 28 years (1993-2021), only 73 peer reviewed researched articles on spatial forest assessment and mapping using remote sensing techniques in Pakistan (Ahmad et al., 2021). Out of which only a hand full were conducted on the mangroves of Pakistan. Many of the studies conducted on Pakistan's mangroves vastly deals with mapping, monitoring, distribution pattern and calculation of mangrove biomass (Sohl et al., 2006).

Myriad studies and independent organizations have provided different estimates of mangrove extents, but all estimates show a decline in their spread. With the help of international (United Nations' project: Reduced Emissions from Deforestations and forest Degradation plus (REDD+)) and national (Pakistan Forest Institute (PFI), Ministry of Climate Change (MOCC), and provincial forest departments) awareness and numerous investments, an upward trend can be seen regarding forest inventory in Pakistan in the form of published reports. However, substantial research gap still exists regarding (1) Utilization of latest and state of the art remote sensing techniques in forest inventory; (2) Employment of different spatial scales (Ahmad et al., 2021); and (3) Complete disregard of mangroves AGB estimation and prediction. Therefore, there is a need for extensive studies on biomass estimation and calculation of mangroves with the help of remote sensing techniques.

1.4. Objectives

This study aimed to:

1. Studied the relationship between AGB derived from ground survey and vegetation indices.
2. Constructed an allometric equation for the estimation of AGB of the mangroves of Keti Bunder.
3. Estimated the amount of carbon storage and CO_2 sequestration of the study area.

Chapter 2

MATERIALS AND METHODS

2.1. Study Area

Keti Bunder (67º 16'E to 67º 32'E longitude and 24º 21'N to 24º 0'N), lying in the Thatta district of Sindh, is about 200 km south-east of Karachi (Tabinda et al., 2010). The river Indus empties up into the Arabian Sea at Keti Bunder. This port of the Arabian Sea covers over 14% (60,969 hectares) of the 600,000 hectares of the Indus delta (Sohl et al., 2006). The climate of Keti Bunder is a typical example of South Asian coasts' climate with short, mild winters (from November to February) and long summer season (from March to October). January has been recorded as the coolest (minimum temperature – 9.5°C) while temperature ranges from 23°C to 36°C in the months of June and July (Rehman, Kazmi, Khanum, & Samoon, 2015). Keti Bunder receives most of its rainfall during the monsoon season (220 mm per year) (Rehman et al., 2015).

Four major creeks namely Chann, Hajamro, Khobar and Kangri are situated in Keti Bunder with countless other small channels on the eastern and western sides (Zaheer et al., 2012). The Indus delta is classified as the 5th largest delta in the world by Ramser Convention on Wetlands 1971. In the past, Pakistan's mangrove forests hosted as many as eight mangrove species. However, due to extreme environmental degradation and numerous anthropogenic factors, four of these species have gone extinct (i.e., *Sonneratia casiolaris, Brugeria conjugata* and *Ceriops roxburghianna*) (Farooqui, 2014). Presently, only four mangrove species remain, with A*vicennia marina* being the most dominant species (90%), followed by *Rhizophora murconata (8%), Aegiceros corniculatum (1.5%) and Ceriops tagal (0.5%)* (Damhoureyeh & Ghalib, 2014).

Keti Bunder is a home to diverse fauna. It houses 69 species of birds (out of which 44 are migratory species), 63 finfish species, 24 shellfish species, 21 reptile species and 2 amphibian species (Damhoureyeh & Ghalib, 2014; Hasnain, 2005).

Keti Bunder houses a cluster of 42 dehs, out of which 28 are believed to be submerged by the sea water inundation. Now it houses a population of 27,405 in 21 dehs and 195 villages (WWF, 2005). In the past, when the flow of fresh water from the Indus River was abundant, Keti Bunder was a rich agro-based area, exporting red rice, bananas, coconut, melon, and watermelon. Now almost 80 % of the workforce is fishers by profession. Other professions include boat owners, boat captains, helpers in factories, drivers, and merchants (Ali, Altaf & Khan, 2016).

The study was focused on selected areas of Keti Bunder as showed in figure 1.

2.2. Data Sources, Quality and Limitation

2.2.1. Field Data Collection

The field data utilized in this study was retrieved during an inventory conducted by Ministry of Climate Change (MOCC) and Pakistan Forest Institute (PFI). The inventory was conducted in the year 2018. Cluster sampling technique was used as it is more suitable in mangrove forest inventory in terms of difficulty in movement due to mud, standing water, pneumatophores, deep water channels and dense underbrush (MOCC, 2018). The size of the plot samples was 0.1 ha (1/10th of a hectare) with a radius of 17.84 m as per standard (Ismail et al., 2018). While the shape was circular. A total of 30 plots are used in this study. Out of which 25 were used in the development of the model while 5 plots were kept for validation purposes.

A Global Positioning System (GPS) device was used to record the sample plot location. The center of the plots was demarcated using a tree or a stone. Whereas a rope was used to demarcate the boundary of the plots.

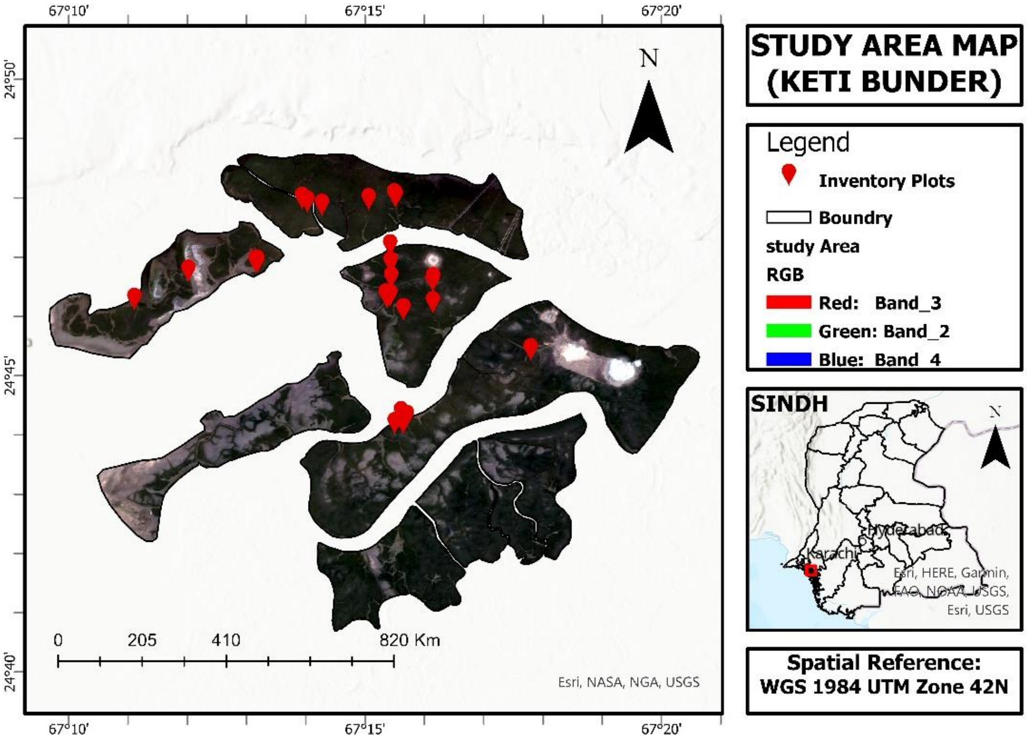

Figure 1. Location map of study area

Following was the information recorded for every sample plot.

- Date
- Recorder name
- Plot number
- GPS coordinates
- Crown cover (%)
- Species name
- Diameter at breast height (DBH) and base (cm)
- Height (m)

Concentric circular plot technique was utilized to measure various carbon pool entities. A subplot of 8.92 m radius was used to measure DBH of trees having diameter ≥ 5 cm. Whereas subplots of radius 5.64 m, 0.56 m were used for measuring shrubs/regeneration and pneumatophores, respectively.

2.2.2. Sentinel-2 Data Acquisition

Sentinel-2B imagery that covered the study area was used in this study. The imagery was acquired on 15th of December 2018 at 6:02:39 AM from Copernicus Scientific Open Access Hub website which is an unrestricted access portal furnishing various products of all Sentinel missions. This Level-2A product was obtained from Tile 42RUN and Relative Orbit 091. Its processing Baseline number is 02.11. Level-2A product is most ideal for research as it is already corrected for top-of-atmosphere (TOA) as well as bottom-of-atmosphere (BOA) reflectance (DE Africa, 2021). The product is a 100x100 km^2 tile which is ortho rectified in UTM/WGS84 projection (EOS Data Analytics, 2017). Further details are provided in table 1. There are three spatial resolutions of Sentinel-2 (10 m, 20 m, and 60 m). 20 m spatial resolution was used as per requirement of plot size (diameter = 35.74 m).

2.3. Analytical Frameworks

2.3.1. Field Above Ground Biomass

Allometric equations have long been used to quantify forest resources by providing estimates of volume, biomass, and carbon of forest stands. Formation of allometric equation is, however, destructive in nature. They are statistical models constructed by measuring various parts of felled tree parts. It uses simple tree measurements like DBH and height to convert into measures like volume and biomass which are difficult to measure on its own (Kassim, Sabri, Kamarudin, & Birigazzi, 2014). Like AGB allometric models, below ground biomass (BGB) models are also widely used to determine the total biomass of a forest stand.

Allometric equations are species specific as well as generalized for specific regions. Nevertheless, species, region/country, climate, and biome specific equations produce more accurate results with minimal error and bias as compared to generic equations (Kassim et al., 2014).

Table 2 and Table 3 comprises of the allometric equations used for the calculation of field AGB and BGB, respectively.

2.3.2. Study Area Extraction and Above Ground Biomass Plots Shapefile

Study area was delineated with the help of editor tool in ArcPro (version 2.8.). The downloaded satellite imagery was displayed in the software and with the help of “edit tool,” the islands’ boundaries were marked. This was saved into a polygon shapefile. Then the bands (Bands 3, 4, 5 and 7) were stacked into a single raster with the help of “composite bands” tool. Then boundary shapefile was used as a clip extent to extract the study area from the composite imagery using the “clip raster” tool.

Table 1. Details of Sentinel data collected.

Satellite	Product type	Sensor	Bands	Resolution	Year
Sentinel-2B	Level-2A	MSI	12	20 m	2018

Table 2. Allometric equations for field AGB.

Serial No.	Species	Allometric equation	Source
1	*Avicennia marina*	$0.1848D^{2.3524}$	(Dharmawan and Siregar, 2008)
2	*Rhizophora murconata*	$0.128D^{2.60}$	(Fromard et al., 1998)
3	Common equation	$0.251\rho D^{2.46}$	(Komiyama, Poungparn, & Kato, 2005)

Remarks: *D*: Diameter at breast height, *ρ*: Wood Density (g/cm^3)

Table 3. Allometric equations for field BGB.

Serial No.	Species	AGB equation	Source
1	Common equation	60% of AGB	(Adame, Cherian, Reef, & Stewart-Koster, 2017)

The AGB from field samples were fed into the excel sheet along with their respective GPS coordinates. The excel file was then imported to ArcPro where the table was then converted into a point shapefile. Both the study area raster and sample plots shapefile were displayed together to better visualize the location of plots on the study area (Figure 1).

2.3.3. Vegetation Indices

Vegetation indices are simple yet effective algorithms which evaluate both qualitative and quantitative characteristics of vegetation such as amount of chlorophyll, plant health and vigor, stage of growth, canopy cover, plant water content to name a few (Xue & Su, 2017). These insights prove immensely useful in terms of conservation purposes, strategic planning and policy, environmental monitoring not only in the field of forestry but others as well like agriculture and urban development.

Vegetation index, in simple terms, is a number derived by computation of two or more spectral bands. This number yield some qualitative or quantitative measure regarding plant characteristics (MapAsyst, 2019). The spectral response reflected from vegetation is captured by the sensor is altered depending upon the physiological changes like plant pigments, water content and growth stage (Liu, Park, & Liu, 2016). However, applicability of a vegetation index depends upon the type of sensor and platform for higher accuracy of results for a particular use (Xue & Su, 2017).

The spectral response of vegetation is immensely different in different spectra i.e. (i) the visible region (comprises of blue (450-495 nm), green (495-570 nm) and red (620-750 nm)), (ii) the ultraviolet region (ranging from 10-380 nm) and (iii) the near and mid infrared region (ranging from 850- 1700 nm) (Rahim et al., 2016). These differences form the basis for inferencing physiological characteristics of plants (Xue & Su, 2017). A total of five vegetation indices were utilized in the development of the model (Table 4). The indices were selected based on their extensive usage in literature and level of performance in bio-physical studies. These indices can be categorized into traditional vegetation indices and mangrove indices. The traditional vegetation indices include Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), Modified Simple Ratio (MSR) and Normalized Difference Index 45 (NDI45). While Combined Mangrove Recognition Index (CMRI) is a mangrove specific vegetation index recently developed by Gupta et al. (2018). They utilized the information derived from Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water index (NDWI) and constructed an improved index which separates mangrove vegetation from other vegetation. They found that there was not much difference between mangroves and non mangroves dominated area when NDWI index was applied as mangroves have high water content in their leaves. When NDVI and NDWI pixel values were subtracted, an increase in the upper and lower range of the output was noticed (Gupta et al., 2018). NDVI is one of the most used vegetation indices to quantify plant vigor, growth, and biomass (Askar, Nuthammachot, Phairuang, Wicaksono, & Sayektiningsih, 2018; Xue & Su, 2017). However, NDVI overestimates in areas of dense vegetation due to saturation (Askar et al., 2018). Replacing the Near Infrared band (NIR) with the red edge band has been proposed as a solution to overcome this problem of saturation (Mutanga & Skidmore, 2004). GNDVI utilizes the green band to show the variation in chlorophyll content of vegetation. MSR is not bounded as its values can exceed 1. NDI45 does not saturate at areas of dense vegetation and is more linear (Soria, Ruiz, & Morales, 2022).

2.3.4. Modelling Relationship Between Field Above Ground Biomass and Vegetation Indices

Coordinates of sample plots in the plot shapefile were used to extract the pixel value of all the indices with a tool named “extract values to points” in ArcPro 2.8. These values were then

Table 4. Vegetation indices used to construct the AGB model.

S. No.	Vegetation indices	Formula	Reference

1	Normalized Difference Vegetation Index (NDVI)	B7-B4/B7+B4	(Kongwongjan, Suwanprasit, & Thongchumnum, 2013)
2	Green Normalized Difference Vegetation Index (GNDVI)	B7-B3/B7+B3	(Isip, Alberto, & Biagtan, 2019)
3	Modified Simple Ratio (MSR)	$(B7/B4)/((B7+B4)^{1/2}+1)$	(Xie et al., 2018)
4	Normalized Difference Index 45 (NDI145)	B5-B4/B5+B4	(Nasiri et al., 2022)
5	Combined Mangrove Vegetation Index (CMRI)	(B7-B4/B7+B4) -(B3-B7/B3+B7)	(Gupta et al., 2018)

correlated with the field AGB and were evaluated based on Pearson correlation coefficient (r) and statistical significance at 0.01. The next step was to construct the AGB estimation model by conducting a stepwise linear regression analysis on the data. Stepwise regression is an iterative process in which the weakest correlated variables are removed and the variables that best explain the model are kept (University of Leeds, 2023). Field AGB was plotted as a dependent variable while the vegetation indices were plotted as independent variables. Correlation and stepwise regression were carried out in SPSS (version 20).

After the formation of the allometric equation for the estimation of AGB, the estimated AGB map was visualized with the help of "raster calculator." The five plots left for validation were then used and their estimated values were compared with the field values. Evaluation was done based on Pearson coefficient of correlation (r) and coefficient of determination (r^2) to confirm the reliability of the model (Figure 2).

2.3.5. Calculation of Below Ground Biomass, Carbon and CO_2

Mangroves have a massive root (pneumatophores) structure to support themselves in the loose, muddy soil. Therefore, their root structure accounts up to 60% of their total biomass (Zhang et al., 2021). BGB stored in the study site was calculated (Table 3). As both predicted AGB and BGB were in g/m^2. Their units were converted to tons/hectare (t/ha) by dividing the AGB and BGB values with 100. The Eq. 1; Eq. 2 and Eq. 3 were applied for carbon stock estimation in the study area. The estimated AGB and BGB were multiplied with their respective carbon conversion factors i.e., 0.48 and 0.39 (Kauffman & Donato., 2012; Aye, Tong, Li, & Tun, 2023). These conversion factors are the carbon concentration percentage in the wood (Kauffman & Donato., 2012). The carbon stock was then converted to sequestered CO_2 by multiplying it with 3.67 (Eq. 4). This value is the ratio of molecular weight of CO_2 and carbon (Kauffman & Donato., 2012).

AGC=0.48*ABG …..........................Eq 1

BGC=0.39*BGB...............................Eq 2

TAC=AGC+BGC..............................Eq 3

CO_2=3. 67C.....................................Eq 4

Where,

AGC = Above Ground Carbon

BGC = Below Ground Carbon

TAB = Total Amount of Carbon

C = Total amount of carbon in study area

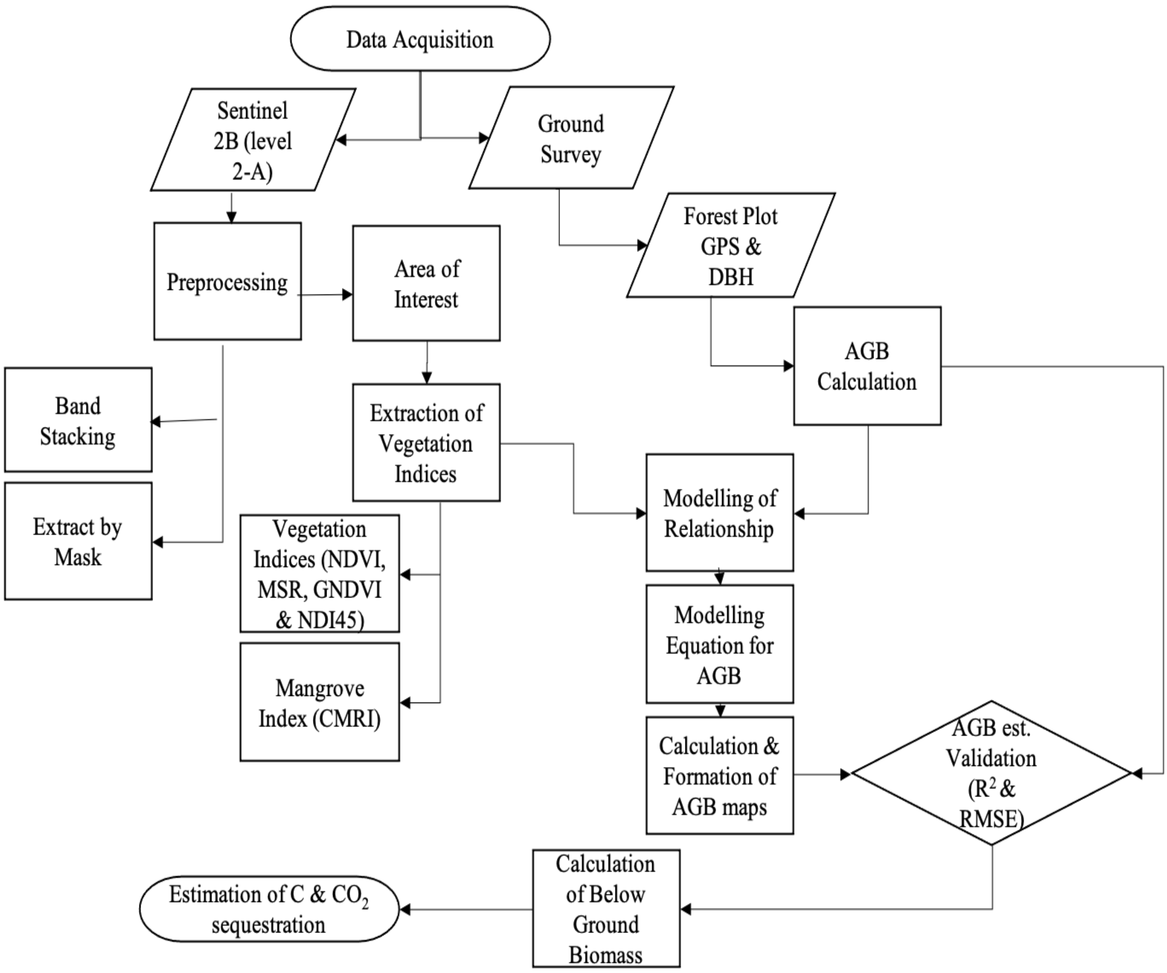

Figure 2. Methodology flowchart

Chapter 3

RESULTS AND DISCUSSIONS

3.1. Descriptive Statistics of Field Above Ground Biomass

The mean of AGB of the 30 plots sampled was 18.3 t/ha, while minimum value was 2 t/ha and maximum values was 61.3 t/ha. Majority of the plots had low to medium amount of AGB. Only 3 plots had AGB more than 30 t/ha and only one plot had more than 45 t/ha of AGB (Figure 3). The reason behind sparse number of plots having high biomass values could be that mangrove's muddy and loose soil terrain is hardy at best. With its extensive and convoluted network of branches, pneumatophores and underbrush, it is quite hard to reach and navigate regions of dense biomass. Therefore, the data showed positive skewness indicating a greater number of smaller values than larger ones. Positive value of kurtosis shows that the distribution is more peaked than normal (Table 5).

3.2. Computation of Vegetation Indices

Vegetation indices were calculated using equations provided in table 4. The bands were input into the raster calculator in ArcPro (2.8.) software. It was found that both NDVI and GNDVI are sensitive to higher biomass density as they could not clearly and distinctly differentiate different biomass density areas (Figure 4; (a) NDVI, (b) GNDVI). They gave higher values in areas of dense biomass but there was not a stark difference between areas of moderate and high biomass density area. However, a stark difference can be seen in areas inundated by water. NDVI showed exceptionally low positive and slightly negative values in areas of still and/or slow-moving water (region coloured yellowish orange) due to its ability to distinguish between vegetation and other surfaces e.g., water (Gerardo & de Lima, 2022). As GNDVI is a modified version of NDVI i.e., replacement of red band with green band, it is considered to have a better potential to assess the chlorophyll component in the leaves having slightly high area index. GNDVI has been vastly used for aquatic plants detection (Gerardo & de Lima, 2022). This finding supports the detection of submerged mangroves or underbrush along the coastlines (yellowish green region). This was not picked up by NDVI. CMRI captured the mangroves distributions as good as GNDVI. It also showed presence of mangroves or underbrush on the outskirts of the islands (Figure 5. (c) CMRI). CMRI while newly developed using Landsat-8, it has been widely utilized by other researchers with different satellite bands. In one study, Chen (2020) achieved 90.74% accuracy while classifying mangroves class from water and land. However, in another study, it has been urged to further verify CMRI feasibility regarding different sites. (Xia, He, Qin, Xing, & Xiao, 2022). Normalized Difference Index 45, in accordance with other research, showed lower saturation in regions of dense biomass. It provided clear differentiation amoung regions of low, moderate and highly dense biomass regions (Figure 5. (e) NDI45). However, it showed lower values for areas which were classified as dense by other three indices. Modified Simple Ratio (MSR) seem to have classified the density of biomass the best. It neither saturated at higher values nor showed lower values at dense regions (Figure 5. (d) MSR).

Figure 6 illustrates scatter plots of field AGB against different vegetation indices. All the indices show a positive trend i.e., as the value of field AGB increases, the value of respective indices also increase. The coefficient of determination (r^2) for MSR was the highest (0.54), followed by GNDVI (0.47), NDVI (0.44) and CMRI (0.45). NDI45 had the lowest value of r^2 i.e., 0.30.

3.3. Correlation Analysis

Correlation analysis is arguably the most common method of statistical analysis. Many types of correlations have been used to for data exploration and modelling. However, Pearson's

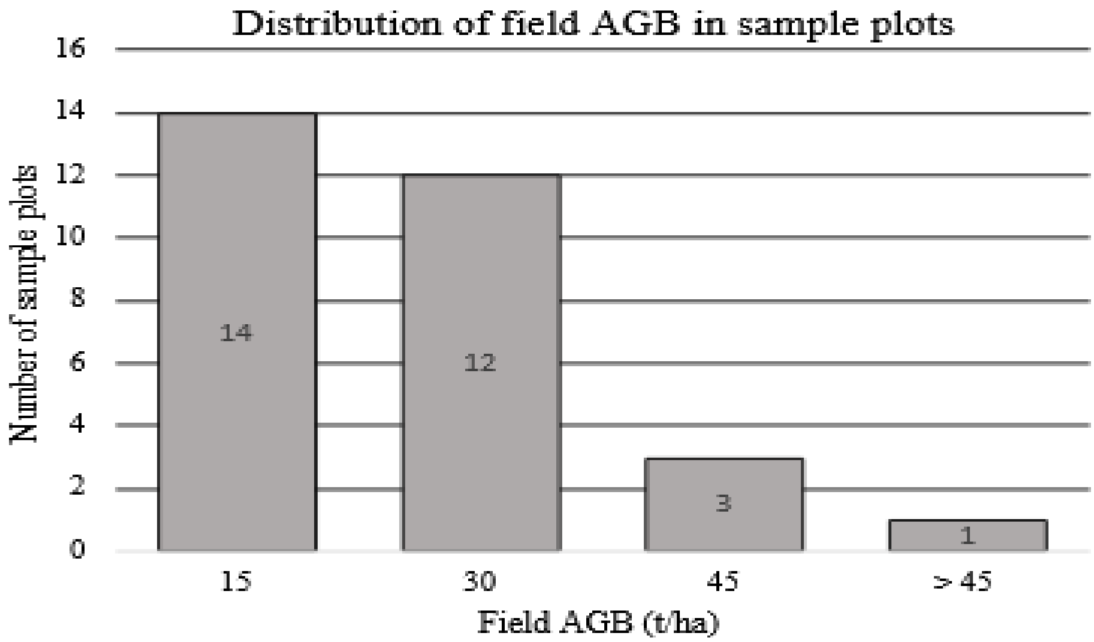

Figure 3. Distribution of field AGB in sample plots.

Table 5. Descriptive statistics of field AGB.

Variable	Max	Min	Mean	SD	Skewness	Kurtosis
Field AGB	61.32	2.06	18.34	13.11	1.3	2.6

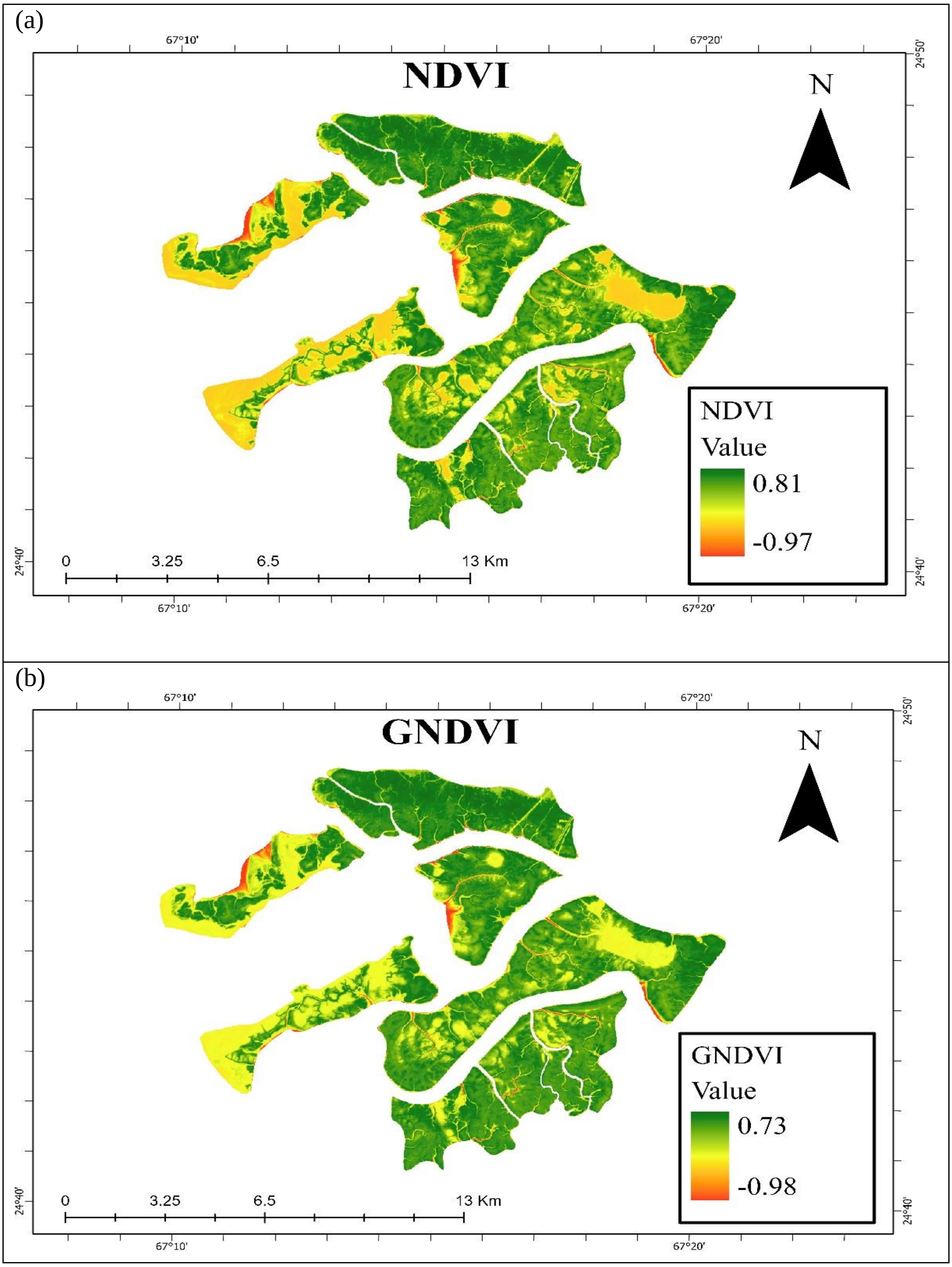

Figure 4. Vegetation indices maps of (a) NDVI and (b) GNDVI.

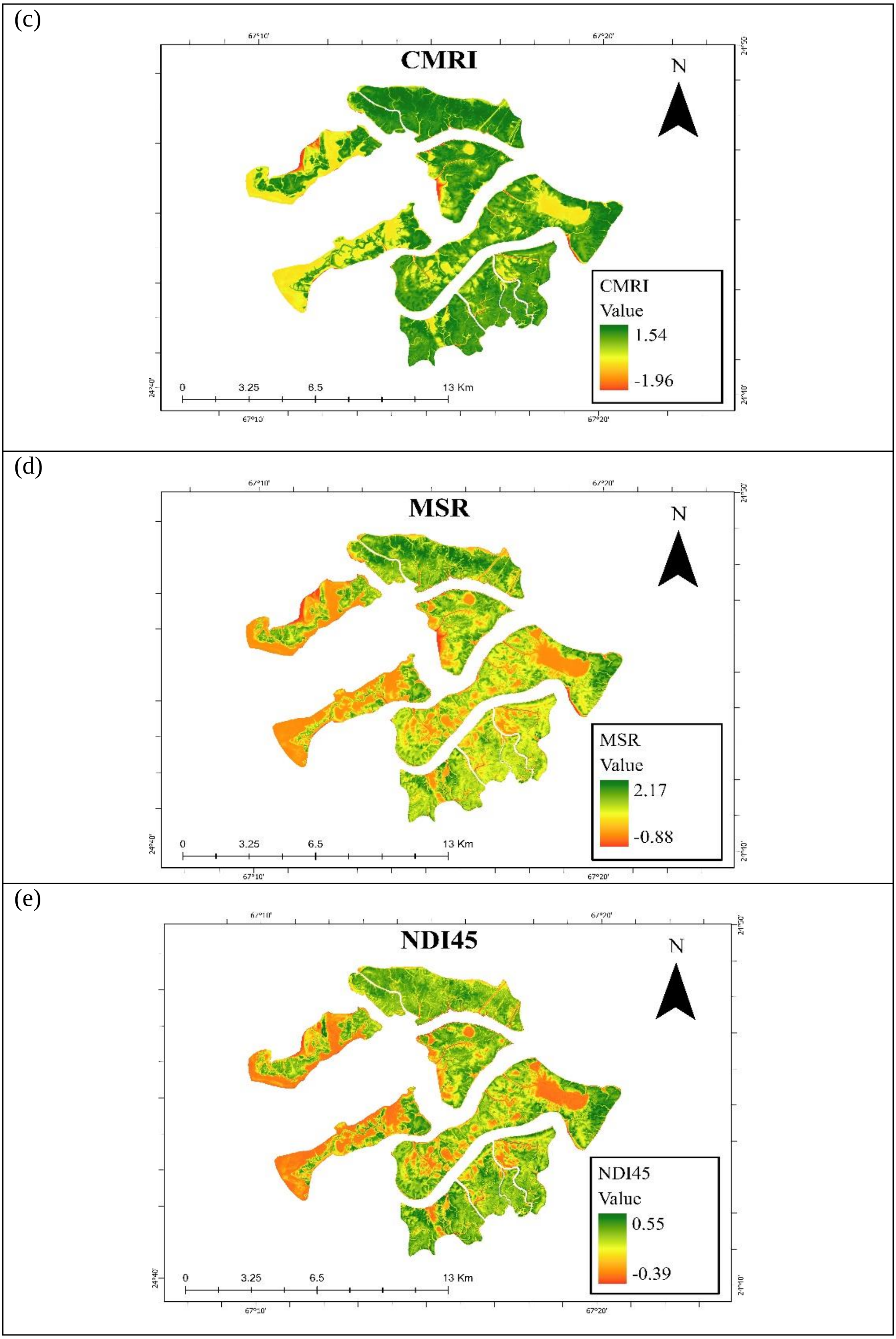

Figure 5. Vegetation indices maps of (c) CMRI (d) MSR (e) NDI45

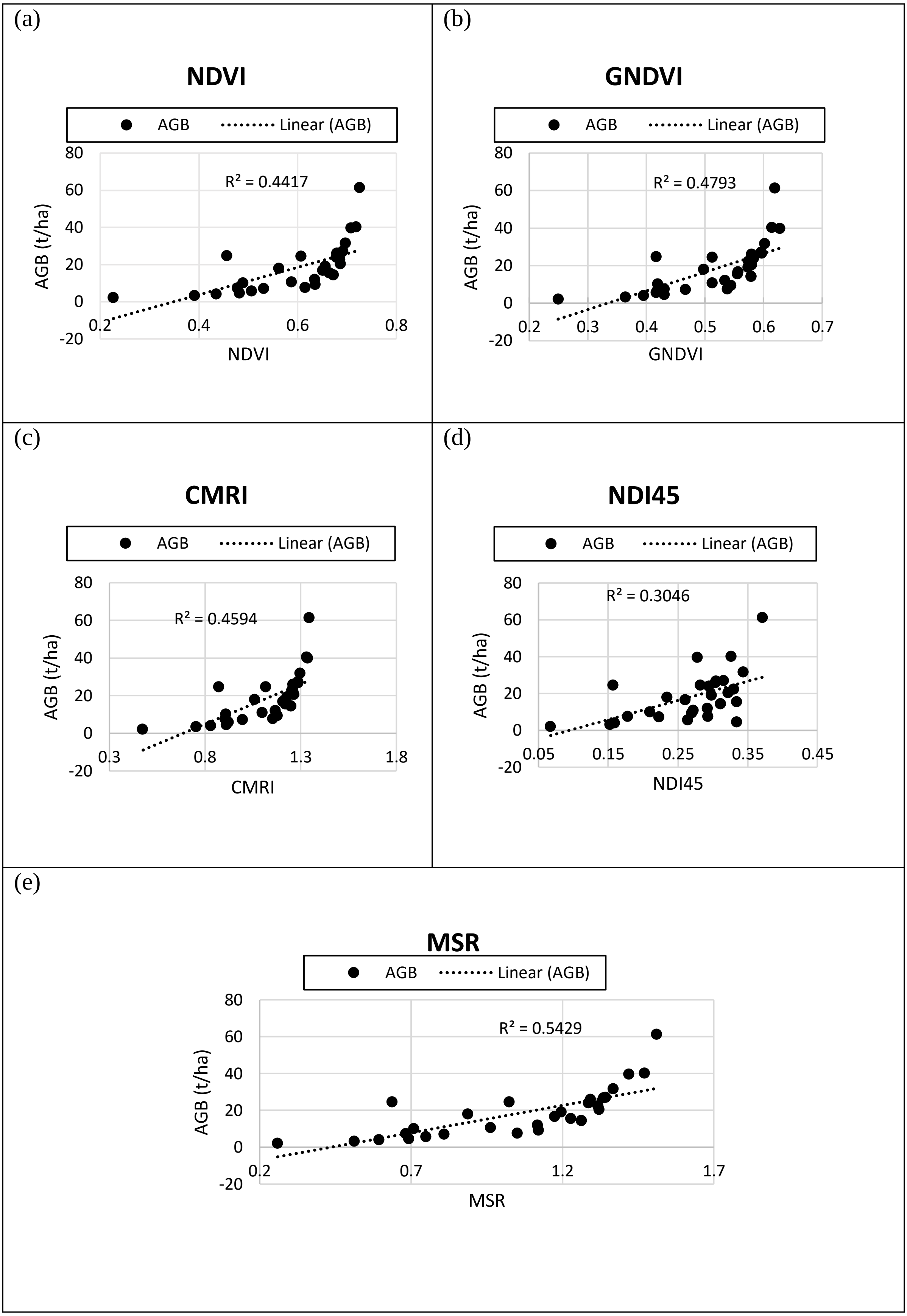

Figure 6. Scatter plots of (a) AGB and NDVI, (b) AGB and GNDVI, (c) AGB and CMRI, (d) AGB and NDI45 and (e) AGB and MSR.

correlation is the most widely used. Makowski, Ben-Shachar, Patil, & Lüdecke, (2020) describe Pearson's correlation as "covariance of two variables normalized (i.e., divided) by the product of their standard deviation". It is a tool for determining the strength of association and direction between two variables (Lindley, 1990, pp. 237–243). Correlation coefficient also known as the Pearson product-moment correlation coefficient (PPMCC) quantifies the strength and direction of the relationship between two variables.

Correlation was carried out amoung field AGB and the vegetation indices. It was found that all the indices were positive related to field AGB with MSR showing the highest level of correlation (i.e., r = 0.73) and NDI45 with the lowest level of correlation (i.e., r = 0.44). The analysis revealed some interesting results. All the indices were highly positively correlated to each other so much so that correlation between GNDVI and NDVI, CMRI and GNDVI and CMRI and NDVI was 0.99. All the indices were significantly correlated to field AGB at 0.01 significance level except for NDI45 which was significant at 0.05 significant level. The result of correlation between field AGB and vegetation indices derived from Sentinel-2 is shown in Table 6.

3.4. Regression Analysis

Chatterjee & Hadi (2013) describe regression analysis as "a conceptually simple method for investigating functional relationships amoung variables". These variables are categorized into dependent and independent variables. In linear regression, the independent variables predict the change in dependent variable for a unit change in independent variable. This change is quantified by coefficient of determination (r^2) which is a measure of goodness of fit of the regression model (Newcastle University, 2023). Table 7 shows the details of linear regression performed on field AGB and vegetation indices. The value of r^2 varied between 0.30 and 0.54. MSR was found to be the best vegetation index in correspondence to field AGB i.e., r = 0.73 and r^2 = 0.54. While NDI45 had the smallest values of r (0.44) and r^2 (0.30).

Stepwise linear regression performed for the development of AGB prediction model is an iterative process of regressing multiple variables while simultaneously excluding the weakest variable. The model developed has the variables that best explain/predict the dependent variable (University of Leeds, 2023). Two models were generated as an output (Table 8). First model only had one independent variable as model predictor i.e., MSR while NDI45 was added as a second predictor in the other model. r^2 and adjusted r^2 are the evaluation metrics used to evaluate the proportion of variance and goodness of fit of the regression model, respectively. As the second model has higher value of r^2 (0.64) and adjusted r^2 (0.61), it means that 61% of the data variations is explained by the second model as compared to the first model which has the value of r^2 = 0.53 and adjusted r^2 = 0.51, explaining 51% of the data variability.

Based on these findings, the second model was opted for estimating AGB in this study. It is expressed as

$$AGB = - 49 + 4005 (MSR) - 9118 (NDI45) \quad \text{…..............Eq 5}$$

Details of the model constructed for AGB estimation are given in Table 9.

Figure 7 illustrates the predicted AGB map constructed by the stepwise linear regression model. It was found that the predicted AGB ranged up to 51 t/ha in the study area with a mean value of 17 t/ha. The map shown in Figure 7 (a) is classified into very low (1-4 t/ha), low (4-14 t/ha), moderate (14-24 t/ha) and high (> 24 t/ha) biomass areas.

3.5. Validation

The five plots not used in the construction of the model were then used to validate the accuracy of the predicted AGB. The field and predicted values of AGB were plotted on a graph The correlation between predicted and observed values of AGB gave a strong coefficient of

Table 6. Correlation matrix of AGB and vegetation indices.

	AGB	**NDVI**	**GNDVI**	**MSR**	**NDI45**	**CMRI**

AGB	1					
NDVI	0.67**	1				
GNDVI	0.71**	0.99**	1			
MSR	0.73*	0.87**	0.84**	1		
NDI45	0.44**	0.98**	0.98**	0.83**	1	
CMRI	0.68**	0.99**	0.99**	0.86**	0.98**	1

Number of plot samples = n = 25; **. significant at the 0.01 level.; *. significant at the 0.05 level.

Table 7. Result of linear regression between Field AGB and vegetation indices.

Serial No.	Vegetation index	r^2
1	NDVI	0.44
2	GNDVI	0.47
3	MSR	0.54
4	NDI45	0.30
5	CMRI	0.45

Table 8. Stepwise regression model summary.

Model	r	r^2	Adjusted r^2	Std. Error of estimate
1	0.734[a]	0.539	0.518	729
2	0.802[b]	0.643	0.611	656

a = predictors: (constant), MSR; b = predictors: (constant), MSR, NDI45

Table 9. Details of AGB estimation model.

Model	Unstandardized coefficients	Standardized coefficients	t	Sig.

	B	Std. error	Beta		
Constant	-49	543		-0.09	0.92
MSR	4005	761	1.2	5.26	0.00
NDI45	-9118	3593	-0.5	-2.53	0.019

Table 10. Collinearity statistics of AGB prediction model

Model	Tolerance	VIF
Constant	1.00	1.00
MSR	0.29	3.38
NDI45	0.29	3.38

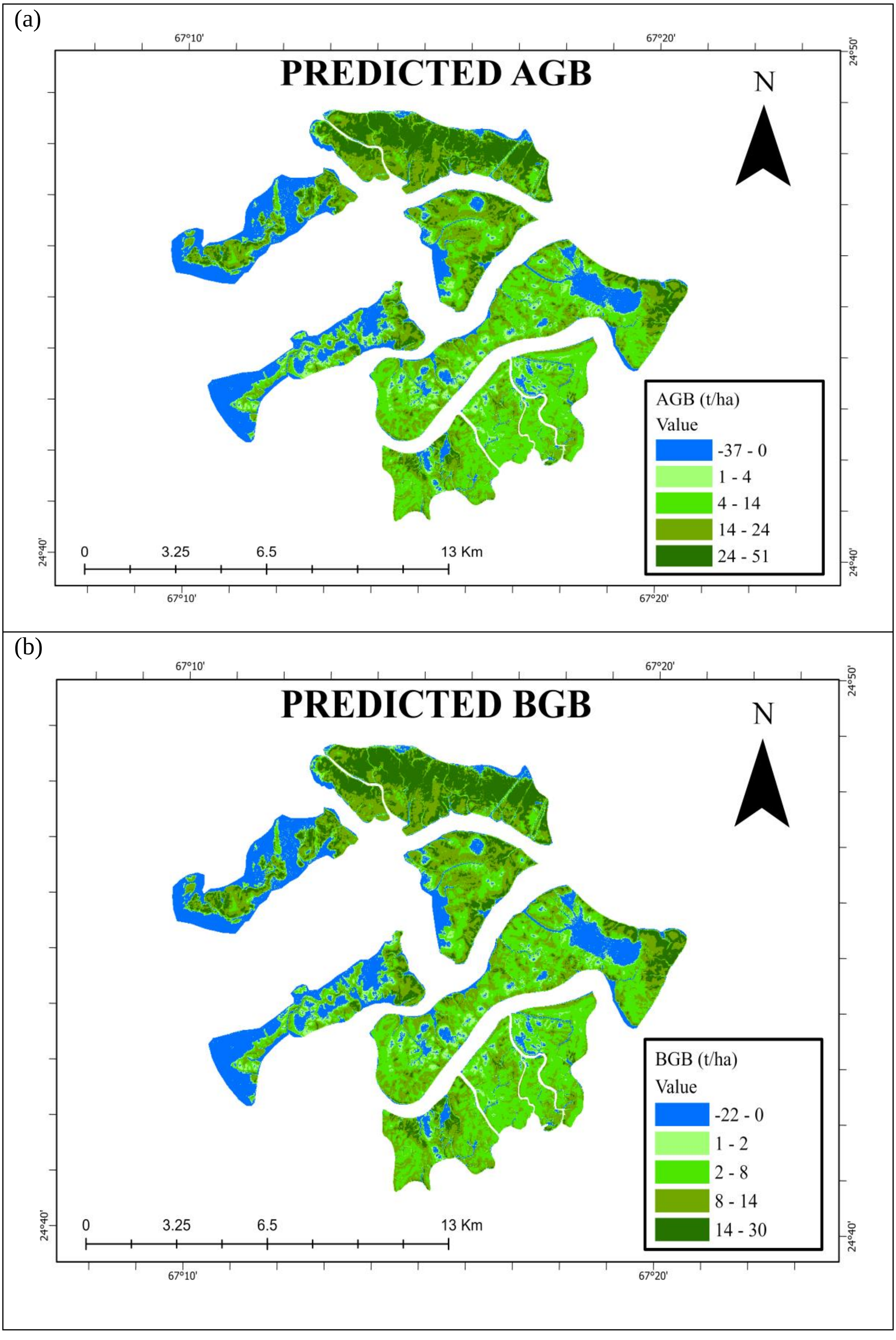

Figure 7. Map of (a) predicted AGB of study area (b) predicted BGB of study area.

determination (r^2 = 0.76). It means that approximately 76% of the observed values were explained by the predicted values (Figure 8). To further strengthen the model, Root Mean Square Error (RMSE) was also calculated from Eq 6. The RMSE was found to be 16.6 t/ha. It was found that the predicted values were quite near to the observed values except those with exceedingly high AGB.

Figure 9 illustrates the difference in observed and predicted values of AGB. An interesting observation was that the observed AGB having high values were largely under predicted while observed AGB having very low values were a bit over predicted but still near the observed values. This is not a multicollinearity problem as the MSR and NDI45 in the model had VIF less than 10 and tolerance value more than 0.2 (Table 10). Such a stark difference in the observed and predicted values of plots with high biomass stems from the little data present for the study. It could also be due to the time difference between when the inventory was conducted and when the Sentinel image was captured as people living near the mangroves harvest trees for commercial and domestic purposes, as well as by the timber mafia.

$$\text{RMSE} = \sqrt{\sum_{i=0}^{n} \frac{(y^\wedge i - yi)^2}{n}} \quad \text{……...............Eq 6}$$

Where

$y^\wedge i$ = Predicted value

yi = Observed values

n = Number of observations

3.6. Below Ground Carbon, Carbon and CO_2 Estimation

Below ground biomass (BGB) was estimated using equation provided in Table 3. It ranged up to 30 t/ha (Figure 7 (b) predicted BGB of study area). The total carbon stock and CO_2 sequestered by the mangroves was calculated by using Eq. 1; Eq. 2; Eq. 3 and Eq. 4. It was found that the total carbon stock of the study area was 36 t/ha whereas the total carbon dioxide sequestered was 133 t/ha (Figure 10 (a) Map of predicted total carbon (b) Map of predicted sequestered CO_2).

3.7. Mangroves of Keti Bunder Survey Responses

An online survey was conducted to assess the awareness of the general public regarding mangroves' benefits and its status. The survey questionnaire was based off on the mangroves of Keti Bunder. A total of 81 individuals participated in the survey. The questionnaire consisted of general information such as gender and level of education, knowledge regarding the existence of mangroves and its direct and indirect benefits, vulnerability status and ways of rehabilitation of mangroves of Keti Bunder.

Out of the 81 respondents, 51% were male and 46% were female with varying educational status i.e., 10% had matriculation level, 20% had intermediate level education while 34% were undergraduates and 36% were postgraduates. The survey showed a wide range of educational status of respondents since out of 81 individuals 76 were informed of mangroves and only 5 were unaware. 90% were aware about its ecological importance while 7% had no idea. 3% said it had no ecological importance. When asked about their knowledge on the protection status of mangroves, 19% said it was well protected, 38% said it required urgent attention while 43% thought it to be satisfactory. When asked about the direct values of mangroves, source of fuel wood and fishing came first, followed by source of income then grazing and browsing and non-wood forest product. Regarding indirect values of mangroves, coastal protection came first, followed by breeding habitat and mitigation against natural disaster.

55% of the respondents had no idea about the level of deforestation in Keti Bunder while 45% claimed to know about its deforestation status.

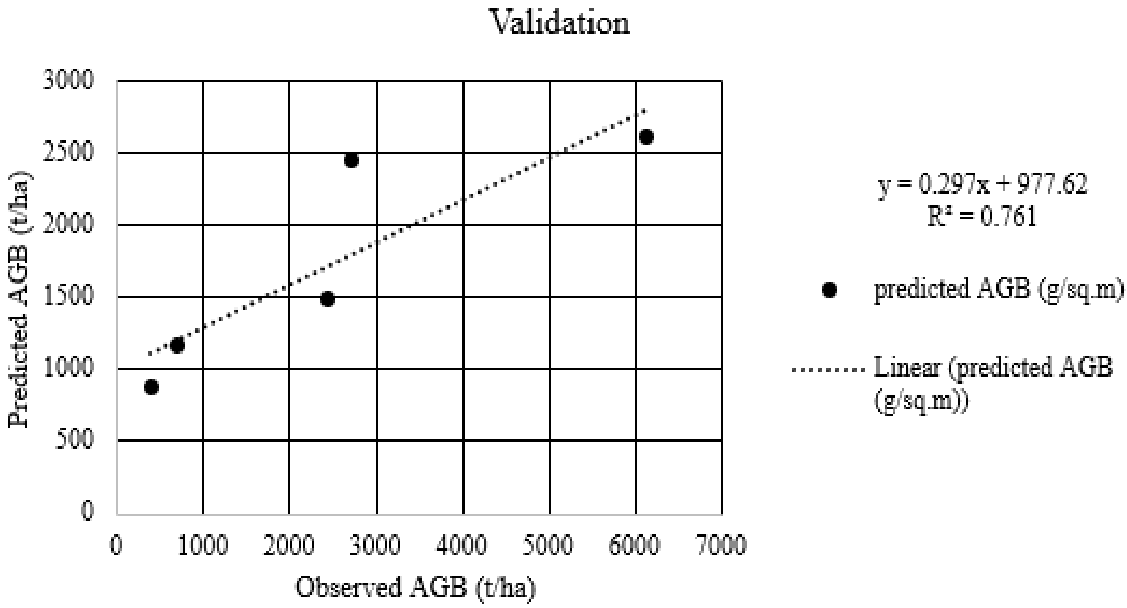

Figure 8. Scatter plot between predicted and observed values of AGB.

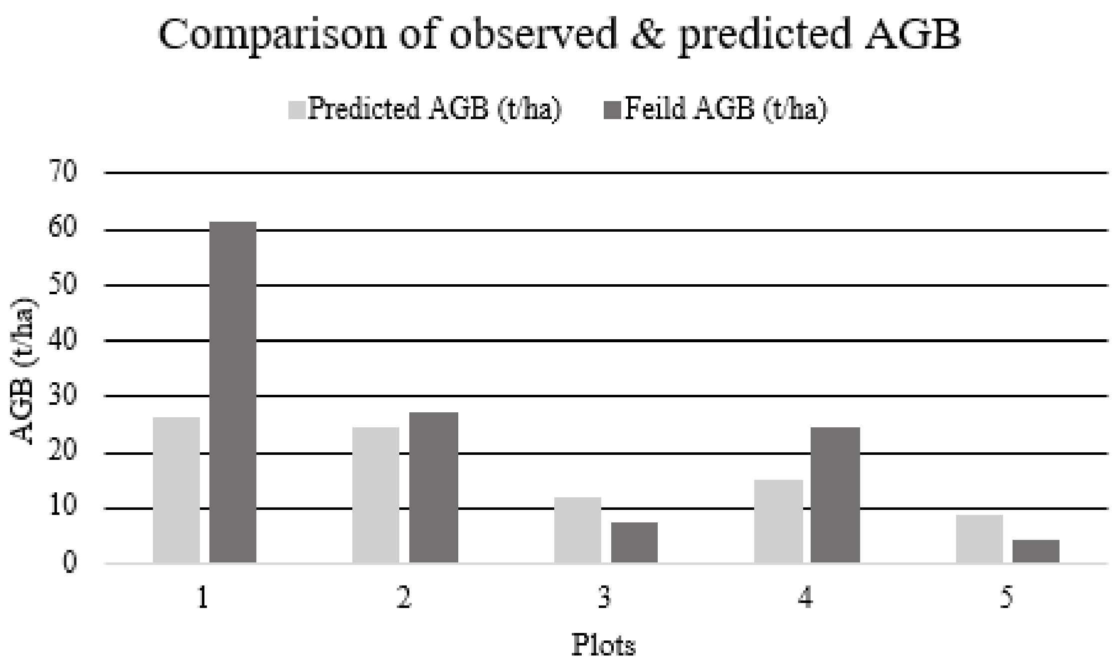

Figure 9. Comparison of observed and predicted AGB values.

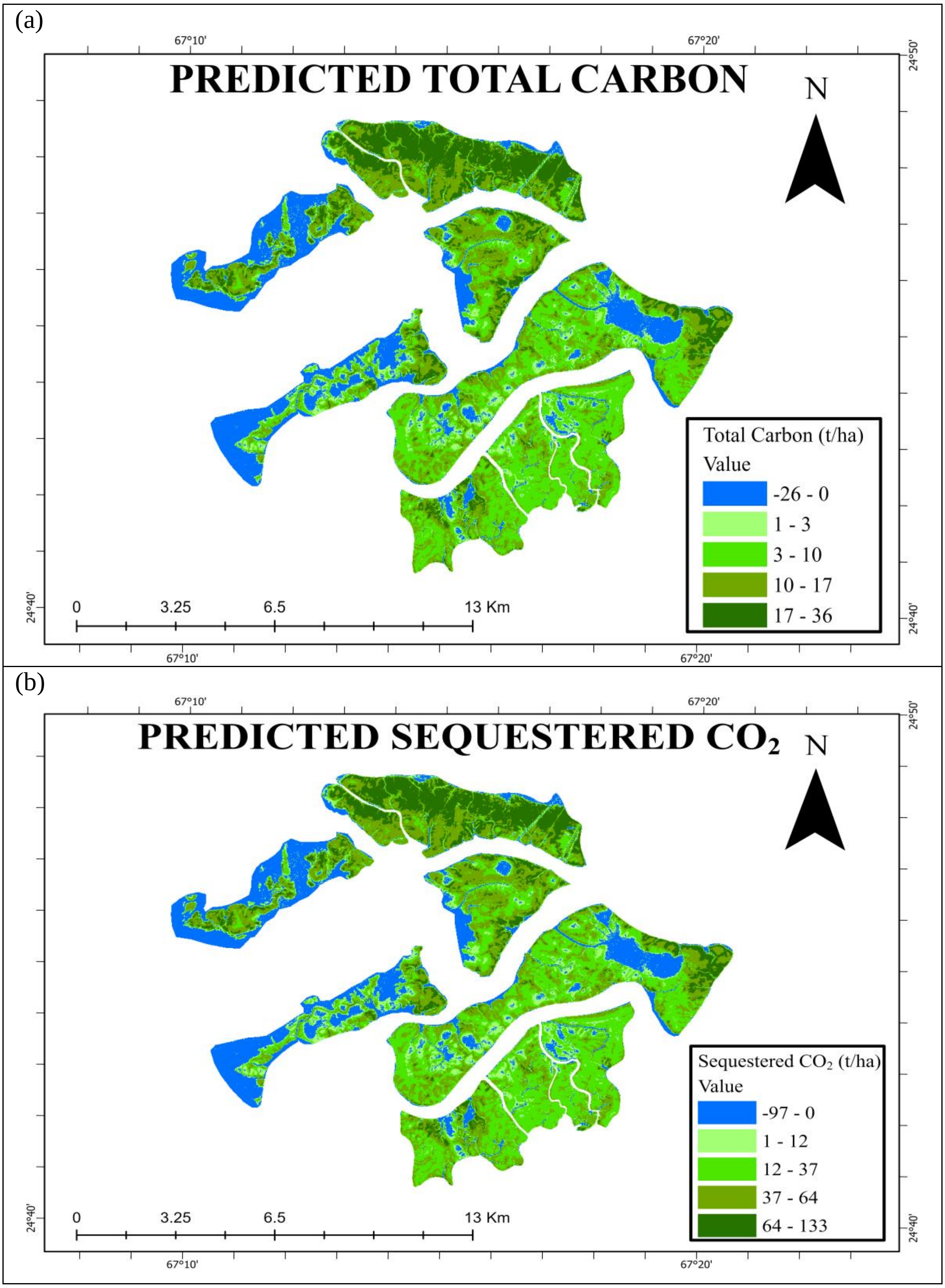

Figure 10. Map of (a) Predicted total carbon (b) Predicted sequestered CO_2

More than half of the respondents were not aware of the status of erosion. Only 32% responded with an affirmative response.

Only 30% of the respondents claimed to have an extreme impact on the livelihood of the natives while 5% completely opposed the claim. Population pressure was thought by 31% respondents to cause degradation of mangroves. Followed by land reclamation, harvesting and some other reasons. Whereas 20% people had no idea about the causes of mangrove degradation. Although it can be assumed that population pressure is the driving factor leading to land reclamation and increase harvest rate. Public awareness (24%) turned out to be the biggest reason behind the lack of mangroves conservation efforts. This opinion can be strengthened since a big percentage of respondents did not have any idea about protection, deforestation and erosion status of mangroves. Political will (20%) was the second most influential reason as Keti Bunder is still an underdeveloped region with its common men highly swayed by their figureheads. Community participatory approach, scientific research, law and legislation and coordination between agencies were opted by 14%, 13%, 17% and 12% respectively.

Better and sure way to conserve the mangroves is to tighten the law and improve the legislature (21%) and its effective enforcement (20%). An increase in the number of programs for public awareness (25%) would not only help in protecting them but also shape the minds of the next generation regarding the specific importance of mangroves.

The responses have been graphically illustrated in Figure 11 and 12.

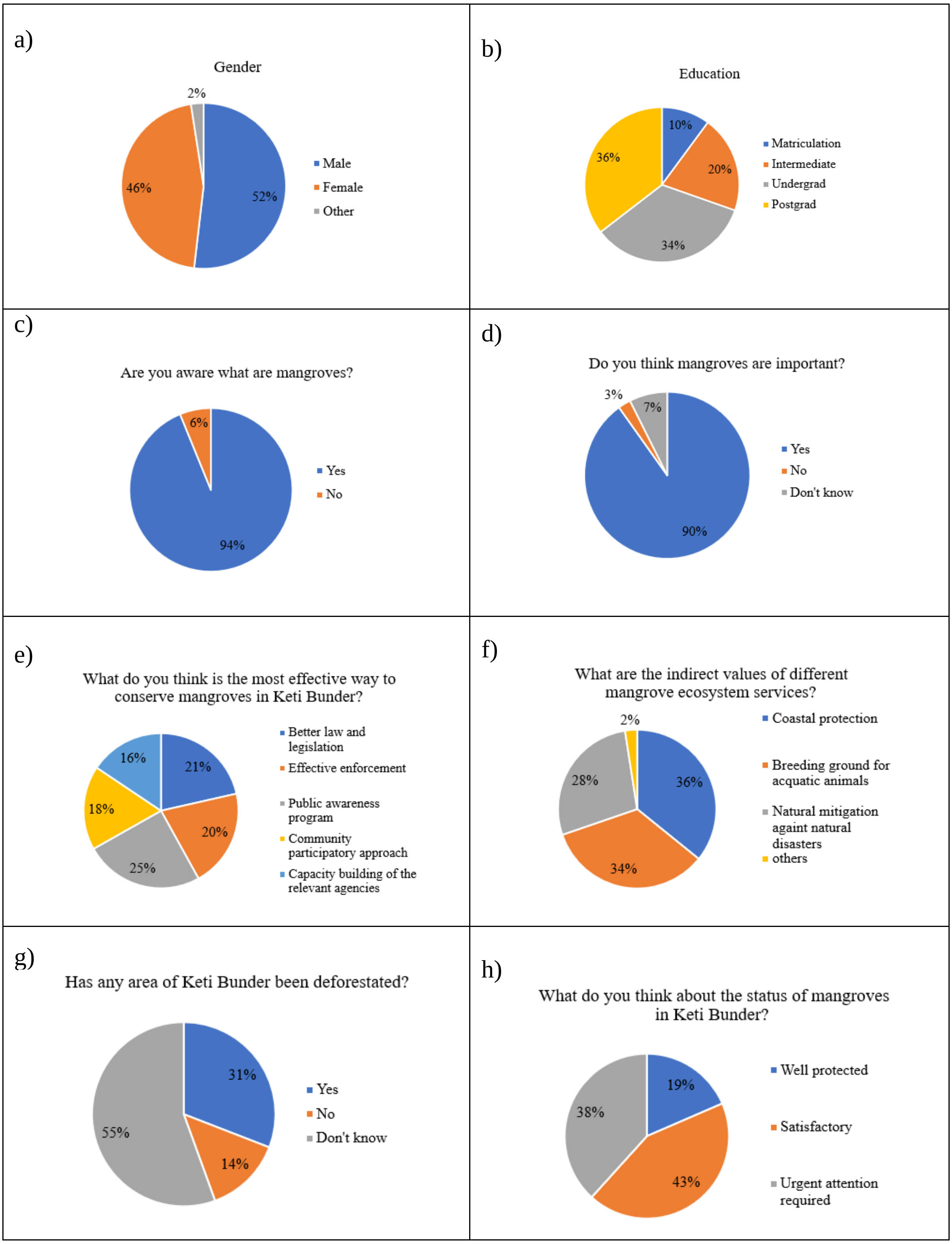

Figure 11. Pie charts illustration of survey responses.

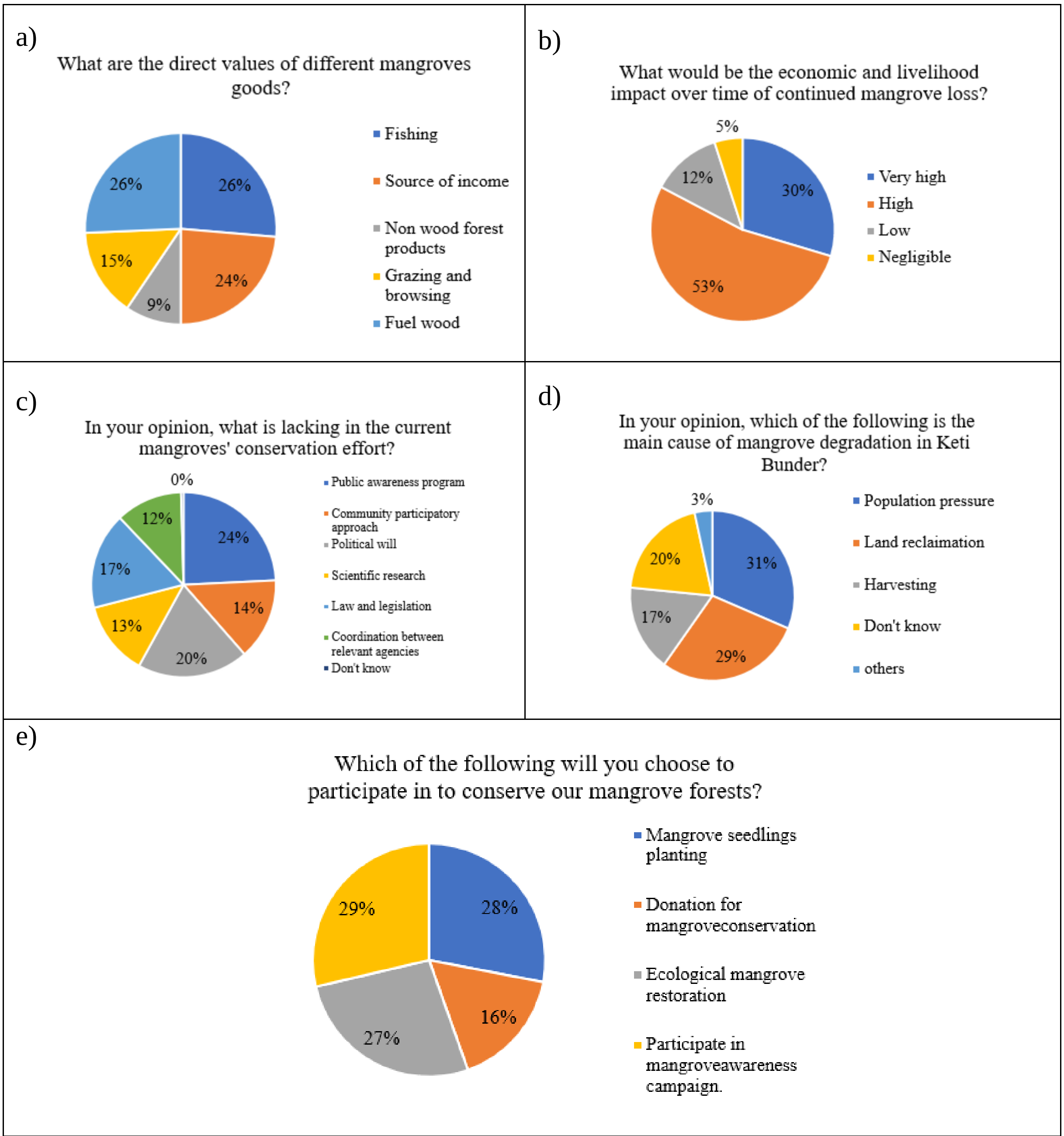

Figure 12. Pie charts illustration of survey responses.

Chapter 4

CONCLUSTION AND RECOMMENDATIONS

4.1. Conclusion

Mangroves with its rich biodiversity provide numerous essential goods and services that play a key role in supporting the community. They regulate the climate, reduce poverty and provide food security. They provide defense against natural disasters like typhoons and tsunami and other extreme weather events by acting as natural seawalls. These blue carbons can sequester exceptional amount of carbon and store it up to a great many years. Despite such significance, they are extremely undervalued compared to other terrestrial forests at the time of policy and decision making regarding coastal development. Even though the benefits derived from mangrove forests are mostly enjoyed by the local/native communities, its degradation and decline effects negatively on whole coastal regions, national economies and world in the form of climate change. While restoration of mangrove forests can rebuild its lost ecosystem services, it is quite time consuming and expensive as compared to the protection and sustainable management of existing mangroves. To attain this objective successfully, information such as latest mangrove protocols, inventory details, changes in coastline topography, knowledge regarding previous failed methods to name a few. However, inventory detail is the key driver of any restoration measure. Volume, biomass, carbon stock and amount of CO_2 sequestrated are all derived from basic measurements like tree DBH and height. As mangroves are found on water inundated, loose, muddy flats, with dense, entwined network of branches and underbrush, it is quite difficult to reach deep into the forests to get samples of dense vegetation on a regular basis. This requires a need for a secondary way to measure its parameters.

This study aimed to formulate an allometric equation derived from the bands of Sentinel-2 image to predict biomass of the mangroves of Keti Bunder. It utilized ground data (DBH of trees in sample plots and their coordinates). Vegetation indices were obtained, and their point values were extracted. MSR showed strong correlation with AGB (r = 0.73) with an equally strong coefficient of determination (r^2 = 0.54). The study revealed that the model constructed for AGB prediction was robust (r^2 = 0.64; adjusted r^2 = 0.61). The AGB predicted from the model also showed promise (r^2 = 0.76). It was found that 76% of the biomass was predicted with high accuracy. The total AGB of the study area was estimated to be up to 51 t/ha with a RMSE of 16.6 t/ha. The results also suggested that mangroves are a sizeable source of atmospheric carbon reduction (up to 133 t/ha).

4.2. Recommendations

The study emphasizes the importance of cost effective and timely assessment of mangrove biomass and carbon stocks at community, regional and international levels. Following are a few recommendations based on the evaluation done in the study.

1. For the better estimation of mangroves biomass, further studies should be conducted regarding different vegetation indices combination and larger ground data.
2. A smaller time gap between the ground inventory and image capture could play a key role in reducing the amount of error.
3. Incorporation of Artificial Intelligence (AI) in the developed model could further strengthen the predictive power of AGB estimates.
4. Promote public outreach and educational plans such as Payment for Ecosystem services (PES) should be promoted at a larger scale to encourage the locals to take up sustainable use and restoration activities.
5. Examine and improve the existing law regarding the protected status of mangrove forests and ensure its strict implementation and penalization on non-compliance.

6. Encourage sustainable farming methods and introduce rotation of species for better conservation.
7. Promote its use as a natural sea wall against natural disasters in coastal development and land use policies.

Extensive research on this study can develop a better and robust method for AGB biomass estimation that can be utilized at national level by the governing bodies. By putting these recommendations into practice, mangroves can be better managed and reforested.

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APPENDICES

Appendix -1: Supplementery material

Data utilized in the study.

Plot No.	Field AGB (t/ha)	NDVI	GNDVI	MSR	NDI45	CMRI
1	61.3262	0.726263	0.619496	1.51123	0.371711	1.34576
2	26.6724	0.690496	0.596505	1.33708	0.305223	1.287
3	20.4888	0.687113	0.579141	1.32209	0.322364	1.26625
4	22.4203	0.686082	0.574578	1.31756	0.330281	1.26066
5	27.1307	0.691859	0.595487	1.34319	0.316062	1.28735
6	25.9432	0.680493	0.579653	1.29339	0.304654	1.26015
7	24.6111	0.456763	0.416457	0.637569	0.157593	0.87322
8	17.9425	0.562121	0.497866	0.888774	0.234795	1.05999
9	31.6358	0.697393	0.601525	1.36838	0.344471	1.29892
10	2.0641	0.226646	0.249123	0.25942	0.067405	0.475769
11	10.0852	0.489804	0.419508	0.70882	0.210052	0.909313
12	40.1935	0.718578	0.614166	1.47118	0.326979	1.33274
13	19.0697	0.656608	0.573641	1.19642	0.298867	1.23025
14	14.3524	0.673284	0.578269	1.26308	0.311385	1.25155
15	14.3655	0.673284	0.578269	1.26308	0.311385	1.25155
16	23.9607	0.678841	0.582666	1.28636	0.294606	1.26151
17	39.7054	0.708455	0.627778	1.42074	0.278499	1.33623
18	16.7247	0.650959	0.556373	1.17485	0.26084	1.20733
19	7.1613	0.531861	0.46645	0.808931	0.222849	0.99831
20	5.7576	0.507605	0.416704	0.749793	0.264727	0.924308
21	4.4986	0.482759	0.430426	0.693123	0.334828	0.913185
22	15.4675	0.66491	0.555399	1.22902	0.334828	1.22031
23	11.963	0.635565	0.533974	1.11848	0.292614	1.16954
24	7.4659	0.478146	0.430158	0.682999	0.178025	0.908304
25	24.4577	0.607686	0.512048	1.02434	0.282577	1.11973

26	9.3575	0.636236	0.544069	1.12087	0.269908	1.1803
27	7.6439	0.61594	0.53826	1.05122	0.293746	1.1542
28	3.2462	0.391539	0.363739	0.512276	0.152651	0.755278
29	3.9825	0.435675	0.394939	0.59501	0.159812	0.830613
30	10.7326	0.58784	0.51203	0.962776	0.272474	1.09987

Appendix-2: Survey questionnaire form

Question No. 1. Please specify your gender.

a) Male
b) Female
c) Prefer not to say

Question No. 2. Please enter your age.

Answer ___________________

Question No. 3. What is your maximum education (Last degree/certificate completed successfully)?

Answer____________________

Question No. 4. Are you aware what are mangroves?

a) Yes
b) No

Question No. 5. Do you think mangroves are important?

a) Yes
b) No
c) Don't know

Question No. 6. What do you think about the protection of mangroves in Keti Bunder?

a) Well protected

b) Satisfactory
c) Urgent attention required

Question No. 7. What are the direct values of different mangroves goods?

a) Fuel wood
b) Grazing and browsing
c) Fishing
d) Non wood forest products
e) Source of income
f) Other

Question No. 8. What are the indirect values of different mangroves ecosystem services?

a) Coastal protection
b) Breeding ground for aquatic animals
c) Natural mitigation against natural disasters
d) Other

Appendix-2 continued

Question No. 9. Has any area of Keti Bunder been deforested?

a) Yes
b) No
c) Don't know

Question No. 10. Has any erosion been noticed?

a) Yes
b) No
c) Don't know

Question No. 11. In your opinion, which of the following are the main causes of mangrove degradation in Keti Bunder?

a) Population pressure
b) Land reclamation
c) Harvesting
d) Don't know
e) Others

Question No. 12. What would be the economic and livelihood impact over time of continued mangrove loss?

a) Very high
b) High
c) Low
d) Negligible

Question No. 13. In your opinion, what is lacking in the current mangroves' conservation efforts?

a) Public awareness program
b) Community participatory approach
c) Political will
d) Scientific research
e) Law and legislation
f) Coordination between relevant agencies
g) Other

Question No. 14. What do you think is the most effective way to conserve mangroves in Keti Bunder?

a) Better law and legislation
b) Effective enforcement
c) Public awareness programs

d) Community participatory approach
e) Capacity building of relevant agencies
f) Other

Question No. 15. Which of the following will you choose to participate in to conserve our mangrove forests?

a) Mangrove seedlings plantation
b) Donation for mangrove conservation
c) Ecological mangrove restoration
d) Participate in mangrove awareness campaign
e) other